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Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis

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ABSTRACT

We calculated carbon and energy balances and costs of 14 different Fischer–Tropsch (FT) fuel production plants in 17 complete well-to-wheel (WTW) chains. The FT plants can use natural gas, coal, biomass or mixtures as feedstock. Technical data, and technological and economic assumptions for developments for 2020 were derived from the literature, recalculating to 2005 euros for (capital) costs. Our best-guess WTW estimates indicate BTL production costs break even when oil prices rise above \$75/bbl, CTL above \$60/bbl and GTL at \$36/bbl. CTL, and GTL without carbon capture and storage (CCS), will emit more CO_2 than diesel from conventional oil. Driving on fuel from GTL with CCS may reduce GHG emissions to around 123 g CO_2/km. Driving on BTL may cause emissions of 32–63 g CO_2/km and these can be made negative by application of CCS. It is possible to have net climate neutral driving by combining fuels produced from fossil resources with around 50% BTL with CCS, if biomass gasification and CCS can be made to work on an industrial scale and the feedstock is obtained in a climate-neutral manner. However, the uncertainties in these numbers are in the order of tens of percents, due to uncertainty in the data for component costs, variability in prices of feedstocks and by-products, and the GHG impact of producing biomass.

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1. Introduction

1.1. Challenges

Transportation contributes 21% of greenhouse gas emissions in Europe and continues to grow [1]. More than 90% of these emissions are due to road traffic, and these have grown by 22% in the period of 1990–2002 [2]. Road transport also produces appreciable quantities of fine particulate matter, volatile organic compounds and other forms of pollution [3]. Environmental problems and other factors, like high oil prices, insecurity about the stability of the oil supply chain and doubts about the sufficiency of oil stocks on the long term put the existing transportation fuel system under pressure.

Consequently, a search is ongoing for alternatives, like new and cleaner fuels. Many alternative fuels, such as biodiesel, DME, ethanol, hydrogen, natural gas and Fischer–Tropsch (FT) fuels have been proposed, researched and compared, see for example [4–9]. Studies have shown that the alternatives that use the lowest amounts of fossil energy and allow for the strongest reduction in greenhouse gas (GHG) emissions require radical and expensive changes in our vehicles and/or fuel logistics. Other alternatives, such as natural gas, or bio-based DME or FT fuels in hybrid cars may require more total energy per km driven than existing systems, but have the potential to reduce GHG emissions considerably [10].

Abbreviations: AIC, annualized investment costs; ASU, air separation unit (oxygen factory); ATR, autothermal reformer (type of natural gas reformer); bbl, barrel of oil (standardized unit; 42 US gallons, 158.9873 l); BFB, bubbling fluidized bed (type of chemical reactor); BTL, biomass-to-liquid; CCS, carbon capture and storage; CFB, circulating fluidized bed (type of chemical reactor); CGP, central gathering point (logistical and intermediate processing facility); CTL, coal-to-liquid; DME, dimethyl ether (CH_3–O–CH_3); DPF, diesel particulate filter; DR, discount rate (measure of time preference in economics); EE, Eastern Europe; EF, entrained flow (type of gasification reactor); EU, European Union; FER, fossil energy requirement; FFB, fixed fluidized bed (type of chemical reactor); FOB, free on board (equipment cost without accessories); FT, Fischer–Tropsch (chemical reaction); FR, forestry residues; GHG, greenhouse gas; GJ_{prod}, gigajoule produced as output of the process ($=10^9$ J); GTL, gas to liquid; GW_{th}, gigawatt thermal input ($=10^9$ watt $= 10^9$ J/s); ha, hectare ($=10{,}000$ m^2); HFO, heavy fuel oil; HHV, higher heating value (includes latent heat of water vaporization); HPC, heavy paraffin conversion (Shell chemical process unit); IGCC, integrated gasification/combined cycle (type of power station); IPCC, Intergovernmental Panel on Climate Change (climate science body); ISBL, inside battery limits (equipment cost with some accessories); JRC, Joint Research Centre (directorate of the European Commission); LA, Latin America; LHV, lower heating value (excludes latent heat of water vaporization); ME, Middle East; MJ_{exp}, megajoule expended as extra input that is lost in the process ($=10^6$ J); MW_e, megawatt electric power ($=10^6$ watt $= 10^6$ J/s); NEDC, new European driving cycle; NG, natural gas (largely methane); O&M, operation and maintenance; OSBL, outside battery limits (equipment cost with most accessories); PM_{10}, fine particulate matter, concentration of particles <10 nm; REE, rapeseed ethyl ester (type of biodiesel); SMDS, Shell Middle Distillate Synthesis (chemical process); SPD, Slurry Phase Distillate (Sasol chemical process); TCI, total capital investment; tonne, 1000 kg (no imperial measurements are used in this paper); TOPs, torrefied wood pellets VAT, value added tax; WE, Western Europe; WGS, water gas shift (reactor, $CO + H_2O \leftrightarrow CO_2 + H_2$); WTW, well-to-wheel; XTL, a combination of coal and biomass to liquid.

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Well-to-wheel (WTW) studies have been published that examine the potential of FT diesel, see [10–13]. However, very few of these have gone into sufficient technological and/or economic detail to make the chains mutually comparable and to trace possible developments into the future. Likewise, modelling studies have been made of (limited sets of configurations of) FT plants but these lack a chain-wide perspective, see [11,14,15].

Therefore, in this article we will make a comprehensive study of the potential of Fischer–Tropsch diesel as a replacement for diesel from crude oil in Europe. We are interested in FT diesel because it is fully compatible with existing vehicles and infrastructure, which is conducive to implementation in the short term. FT diesel can be made from a wide range of feedstocks, including natural gas, coal and biomass, allowing for a gradual transition between energy sources. FT diesel is well suited to the existing market, as FT diesel has a high cetane number and does not contain sulphur or nitrogen. At the same time, the market share of diesel fuels in the EU is expected to grow considerably, while marginal fossil diesel production at EU refineries is stretched and relatively inefficient and oil prices may remain high [10,16,17]. This situation presents an entry point for the FT alternative.

1.2. History and current activities

Fischer–Tropsch fuel production was first started in 1935 at the Ruhrchemie company. A total of nine plants were built in Germany, and shut down in 1945. These were coal-to-liquid (CTL) plants [18]. After WWII, Fischer–Tropsch (FT) fuels have been produced primarily from coal in South Africa, in order to reduce the nation's dependence on foreign oil. The economic success of the Sasol plants in South Africa largely coincided with the relatively high oil prices in the late 1970s and early 1980s that made investment in synthetic fuels favourable [19]. Investment costs were otherwise prohibitive [20]. From the early 1990s, gas-to-liquids (GTL) plants have been constructed to use natural gas as feedstock, to capitalize on (what were at the time) stranded gas reserves [21]. Commercial activities have thus historically been limited to situations where feedstocks were cheap and liquid fossil fuels were expensive.

The only FT fuel that was commercially available in 2007 in the EU is GTL product from the Bintulu plant which is a constituent of the V-Power brand from Shell. As of 2007, companies like Shell, Sasol Chevron, ConocoPhilips and Total are all working on GTL and CTL plants. Large scale GTL activity is underway, especially in Qatar [22,21]. In addition to confirmed projects, large CTL plants in China (for example in Ningxia Hui) and India are being planned (ibid.). CHOREN industries in Germany and others experiment with the use of biomass as a feedstock for FT fuel production (biomass-to-liquid or BTL) [23].

Development of FT production could also benefit from improvements in technologies such as gasification and gas cleaning that are used in other commercial activities. However, due to the large projects and investments involved, the speed of implementation of new technologies is limited (see Dry [19], for example).

1.3. Research questions

This paper aims to trace development path for FT diesel, based on data on existing technologies and bottom-up simulations of new technologies. For the narrative in this paper, it is assumed that increases in diesel demand will be covered to a significant degree by FT fuel plants, fed initially with natural gas and coal, but increasingly with biomass. Potential WTW chains will be compared with regard to cost and the emissions of GHG for various options to produce FT diesel with existing and emerging technology (such as carbon capture and storage). We aim to answer the following questions:

- What are the (main determinants of) GHG emissions and costs of FT based chains?
- What competitive and climate-friendly FT chains can replace fossil-based diesel?

In Section 2 of this paper we will describe the methodology used to analyze WTW chains. Section 3 details our source data on feedstock supply, conversion to FT fuel and distribution, and driving. The resulting configurations and chain-wide results are examined in Section 4. Variations and uncertainties in the results are discussed in Section 5. The results are summarized and conclusions drawn in Section 6.

2. Methods

2.1. Well-to-wheel chain analysis

The methodology to make WTW comparisons is essentially a specialized form of comparative life-cycle analysis. The functional unit in this study is 1 km of transportation delivered in an average EU car. To make a fair comparison between technology options, resource requirements, emissions and costs should be considered over the entire well-to-wheel (WTW) chain, as presented in Fig. 1.

In this study, the total chain energy use (MJ/km), fossil and renewable energy requirement (MJ/km), cost (€/km), GHG emissions (g CO_2equivalent/km) are calculated as follows:

Energy use is determined by accumulating resource requirements from wheel to well, thus starting from driving:

$$e_{\text{total}} = e_{\text{driving}} * (1 + e_{\text{distribution}}) * (1 + e_{\text{conversion to fuel}}) * (1 + e_{\text{conversion to intermediate}}) \quad (1)$$

We assume that distribution uses the diesel produced in an earlier step and that conversion plants do not require energy inputs other than the main feedstock. The latter is not entirely true in the real world [10,24] but greatly simplifies the analysis.

- For local transport at the source and long range transport, energy use is counted as separate fossil energy input. Local transport is assumed to use diesel, and long range transport is assumed to use heavy fuel oil (HFO) for ships and diesel for trains. CO_2 emissions from fuel production are accounted for.

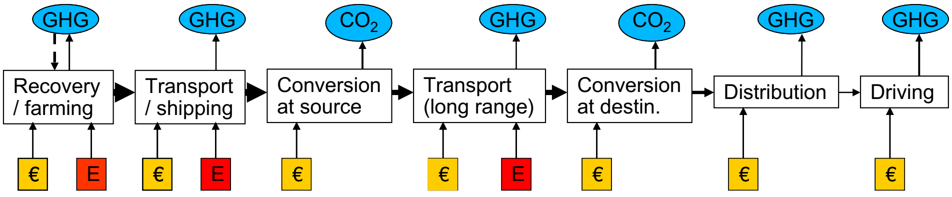

Fig. 1. WTW analysis: chain inputs and emissions (E = fossil energy, € = money).

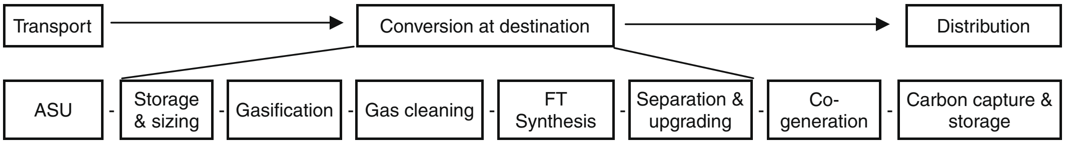

Fig. 2. Example of the breakdown of a conversion link (Fig. 1) into process units, for the case of a BTL plant.

- Recovery/farming energy is counted as fossil energy input. Production inputs are accounted for on a case specific basis because of the divergent nature of the feedstocks.
- GHG emissions for recovery/farming include sequestration effects for biomass. We assume that it is possible to make biomass available for the BTL process in a carbon neutral way.

Ideally, energy and materials included in the construction of facilities, infrastructure and vehicles should also be included. It is known that around 80% of the energy for a conventional petrol-driven car comes from fuel. The remaining share comes from manufacture, maintenance and end-of-life [25]. Because the variation in vehicles is kept to a minimum in this study (all are functionally equivalent) and the aim is to provide a comparison rather than absolute numbers, only the driving share of energy is taken into account in this study.

All GHG emissions of fuels used (also in transport) are calculated to include conversion from primary feedstocks (oil, natural gas, coal or biomass). We use production data for fossil diesel and HFO from Edwards et al. [10]. Non-CO_2 GHG emissions are also taken into account as CO_2 equivalents, as far as our data sources include these. Non-GHG emissions are not taken into account, with the exception that future diesel vehicles are assumed to have a particulate filter.

Because FT diesel can be used in the same engines that use fossil diesel, the chains have largely the same tank-to-wheel (TTW) parts. By contrast, the well-to-tank (WTT) parts are quite dissimilar. Seven basic WTT chains, eventually giving rise to 17 WTW variants that could be relevant for Western Europe, are addressed in this paper:

1. Crude oil – shipped to Western Europe – refined to fossil diesel.
2. Natural gas – converted to FT fuel – shipped to Western Europe.
3. Coal – sent to port – shipped to Western Europe - converted to FT fuel.
4. Biomass – converted to pellets – sent to port – shipped to Western Europe – converted to FT fuel.
5. Biomass – converted to pellets – sent to port – converted to FT fuel – shipped to Western Europe.
6. Biomass – converted to FT fuel – sent to port – shipped to Western Europe.
7. Biomass – converted to TOPs – sent to port – shipped to Western Europe – converted to FT fuel.

The complete set of chain variants is defined in Section 4.

2.2. Well-to-wheel chain links

In order to construct chains that reflect dynamic future development, narrative scenarios are constructed to provide a real-world reflection on the changes. The scenarios aim to address the aspects of each chain link that most strongly determine cost, energy efficiency and GHG emissions. Initially, these include feedstock choice, feedstock availability, as well as the scale of conversion plants, the applicability of carbon capture and storage (CCS) options and improvements in technology of FT synthesis plants and vehicles.

However, the chain links described in Fig. 1 represent aggregated processes. In order to take into account specific technological advances, for instance in catalyst chemistry or gas turbine design, a link must be disaggregated to a point where individual technologies can be distinguished. A conversion plant is therefore broken down to process units, which can be described and modelled as connected but more or less independent process units. Supporting units, such as an air separation unit and power island also need to be considered. For a chain with a BTL plant, Fig. 1 could break down into units as depicted in Fig. 2.

In theory, the various process steps such as gasification, gas cleaning and synthesis, are easily distinguished. In practice, secondary flows, such as heat, electricity, oxygen, hydrogen and carbon dioxide mean that the sub-processes are closely linked. In one case, 15 or more flows move back and forth between gasifier and synthesis unit [26]. Analogous disaggregated descriptions can be made for biomass production and transportation (see [27,28]), or oil refining.

2.3. Calculation methods

Formulae and assumptions that are not specific to a specific chain link are described below. Those that are specific to a single link are listed with the data for that link.

The conversion facilities (Fischer–Tropsch plants, pelletizing plants) are modelled with mass and energy balances in an Excel spreadsheet. Equipment costs, efficiency data and energy requirements were obtained from literature and the units are scaled to match the throughput. The total capital investment (*TCI*) is calculated using factored estimation [29]. With this method, a large installation is divided into discrete major components. The total capital investment is equal to the sum of the costs (*C*) of each of these components, with an added installation factor[1] (*f*) for relevant infrastructure, piping, controls, etc., and increased by 15% for contingencies.[2]

$$TCI\ (€) = (1 + 0.15) * \Sigma C_i(1 + f_i) \tag{2}$$

Engineering costs (planning, installation, O&M) are expected to decline as designs mature. Current designs are already being copied to reduce engineering costs: Sasol essentially duplicated the 1977 Secunda facility for its 1983 East Plant facility [32], and Sasol–Chevron's new plants in Qatar and Nigeria use standardized integrated process units [33].

A load factor of 8000 operating hours per year is used in almost all our calculations to factor in maintenance downtime. For every operation in the chain, the scale is an important determinant of costs. Scaling factors from literature are used for each of the components. The costs of the components are scaled using following formula (3):

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[1] Equipment costs quoted in literature come as one of the following [11]:
- Free on Board (FOB), for a bare process unit that is package and ready for transport;
- Inside Battery Limits (ISBL), which includes piping, instrumentation, etc;
- Outside Battery Limits (OSBL), which also includes land cost, power lines, sewage, etc.

Installation factors therefore vary widely and are specific to each quoted price.

[2] We use higher contingencies than the 10% indicated by [30,12] or [31], but we do not include R&D costs.

$$\text{Cost}_{\text{original}}/\text{Cost}_{\text{Scaled}} = (\text{Size}_{\text{original}}/\text{Size}_{\text{scaled}})^{\text{Scaling factor}} \tag{3}$$

For costs stemming from the installation factor, a generic scaling factor of 0.82 is used in our study [34]. The scaled investment costs are annualized through formula (4) (DR% = discount rate percentage). To arrive at the total annual costs, 4%[3] of TCI is added as O&M costs. Electricity sales and CO_2 credit revenue (if any) are subtracted from the production costs. The annual costs are divided by the sum of naphtha and diesel production to calculate costs per unit of fuel.

$$\text{Annualized Investment Costs } (€) = TCI/(1 - DR\% + 1)^{-\text{Lifetime}} \tag{4}$$

$$\text{Total Annual Costs } (€) = AIC + TCI^{*}4\% - \text{Electricity Sales} - \text{Carbon Credits} \tag{5}$$

$$\text{Cost of Fuel } (€/GJ) = \text{Total Annual Costs}/(\text{Synfuels Production}) \tag{6}$$

Process energy requirement and CO_2 emissions are allocated between diesel, petrol and exported electrical power on MW LHV and MW_e basis.[4]

$$\text{GHG of Production } (CO_{2eq}/GJ) = (\Sigma\text{Process Emissions} - \text{Electricity}_{\text{baseline}})/\text{Synfuels Production} \tag{7}$$

Harmonised EU-25 average consumer price indices from 1996 to 2005 [38] are used to compensate for inflation in data from before 2005. Costs in non-Euro currencies are converted to euro first[5] and corrected for inflation afterwards. The cost per ton of avoided CO_2-equivalent emissions is defined as follows, using WTW €/km and CO_{2eq}/km values as input:

$$\text{Cost of } CO_{2eq}\text{avoided } (€/\text{tonne}) = (\text{Cost}_{\text{case}} - \text{Cost}_{\text{reference}})/(\text{Emissions}_{\text{reference}} - \text{Emissions}_{\text{case}}) \tag{8}$$

Diesel used in the supply chains is assumed to cost 1 €/l [40] and emit 3917 g CO_{2eq}/l. Heavy fuel oil is assumed to cost 0.20 €/l and emit 4210 g CO_{2eq}/l.

3. WTW input data

We will first outline the data used for baseline oil-based diesel production and then detail the data related to (a) feedstock supply and logistics chains, (b) Fischer–Tropsch conversion plants and (c) distribution and driving.

3.1. Oil-based diesel production

The baseline fossil diesel in this paper is assumed to be made from Middle East oil. The technology for refining oil is evolving: refineries increase their efficiency by around 1% per year [10]. This advance is negated at least in part by the increasing use of sour and heavy crude oils that require more effort to process and by increasingly stringent fuel specifications [6]. Here we assume that the former trend cancels out the latter: All refineries use 0.1 $MJ/MJ_{\text{diesel produced}}$ and emit 8.60 g $CO_{2eq}/MJ_{\text{diesel produced}}$ [10].

The oil price for the base case is 60 $/bbl (price developments and their impact are addressed in the Discussion section). The cost of refining fossil diesel is often quoted in relation to the price of crude oil. The price markup from refining is estimated at 20% [41] to 39% [42]. We assume a constant markup of 30%.

3.2. FT feedstock supply and logistics

We make FT fuels from three feedstocks: coal, natural gas and biomass (though use of the latter is at present still in a pre-commercial stage). The following options for feedstock and conversion choices are considered:

3.2.1. Fossil feedstocks

Both coal and natural gas are established commercial feedstocks for FT. Two examples are the Shell plant in Malaysia that uses stranded gas reserves and the Sasol plants in South Africa that use coal and natural gas.

Coal is assumed to be shipped to Europe from mining sites. Due to advantages of scale in port facilities, coal is converted in a large, centralized conversion plant. We use supply chain data for bituminous coal from [10]. The production and delivery of bituminous coal requires 0.096 MJ/MJ_{produced} and emits 15.33 g $CO_{2eq}/MJ_{\text{produced}}$. The cost of coal at the conversion plant gate is assumed to be 2.01 $€_{2005}$/GJ [17].

Natural gas is assumed to be produced in the Middle-East, a region with very large gas reserves [43]. It is locally converted to FT diesel and shipped to Europe. The production of natural gas requires 0.024 MJ/MJ_{produced} and emits 3.59 g $CO_{2eq}/MJ_{\text{produced}}$. The cost of natural gas at the conversion plant gate is assumed to be 1.05 $€_{2005}$/GJ.[6]

3.2.2. Biomass feedstocks and intermediates

Biomass differs from oil and gas in that it is not recovered from a point source, but from a distributed area. After collection, it is driven by truck to a central gathering point (CGP), where it is processed. We assume that biomass supply develops as follows: At present, there are no large amounts of excess biomass available close to Western Europe (WE). The BTL chain therefore uses remote and thinly spread out residues from the forestry industry in Canada.

We also assume that by 2020 sustainable biomass production has been set up in Eastern Europe (EE, Ukraine or Romania), Latin America (LA, southern Brazil) or East Africa (Mozambique, treated as similar to LA), centred around plants that convert the wood to pellets for shipping to WE. Alternatively, wood is still converted to pellets to facilitate transportation, but the conversion to FT fuels is done at a facility on the Black Sea coast (EE) or on the Atlantic coast (LA). In LA biomass can also be converted to torrified wood pellets (TOPs) in modified pelletisation plants or converted directly to FT diesel at smaller FT plants in the farming areas.

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[3] Edwards et al. [10] indicate a range of 3% (low-tech) to 4.5% (high tech). Larson et al. [35] and Hamelinck et al. [36] use 4% O&M as well.

[4] The exported electrical power is equal to the total generation minus the electricity required to operate the conversion plant including any CCS equipment, if used. CO_2 emissions of the FT plant are credited with replacing emissions from baseline electricity production of 560 g CO_2/KWh in Western Europe (based on the Dutch power mix), 324 g CO_2/kWh in the Middle East (based on a 60% efficient natural gas combined cycle plant) and 0 in biomass growing areas (because biomass would produce carbon neutral electricity. Energy input for the FT plant is credited with the energy input from baseline electricity, which is calculated by dividing the exported electricity by the assumed generation efficiency of a stand-alone combined cycle power plant (40% in Western and Eastern Europe with CCS and 45% without, 60% in the Middle East, 40% on the coast in Latin America and 35% at a CGP), based on Damen et al. [37]. The impact of the allocation method is especially strong in the case of natural gas fed FT plants.

[5] We use Interbank currency exchange rates, averaged over the entire year [39].

[6] Based on the cost for LNG in Japan of Middle-East origin [17] and assumes that the cost of producing natural gas and bringing it to a seaside terminal is 20% of the total cost of supplying natural gas to a foreign terminal [43]. The cost of 1.05 €/GJ assumes the gas could be exported. Stranded gas costs can be as low as 0.17 €/GJ [44].

Table 1
Data, cost, energy use, and GHG emissions for farming of biomass and conversion at central gathering point used in this study.

Biomass supply chains-farming and CGP input data	Canadian FR to pellets to WE	EE salix to pellets to WE	EE salix to local BTL	LA eucalyptus to pellets to WE	LA eucalyptus to local BTL	LA eucalyptus to TOPS to WE	LA eucalyptus to CGP BTL
Time frame	*Present (2005)*	*Future (2020)*					
Biomass	Quebec forestry residue	Eastern Europe salix	Eastern Europe salix	Latin America eucalyptus	Latin America eucalyptus	Latin America eucalyptus	Latin America eucalyptus
Coverage (% of land used for biomass production)	100%	30%	30%	30%	30%	30%	30%
Production density (tonne/ha)[a]	0.0048	3.7	3.7	5.74	5.74	5.74	5.74
Production cost (€2005/tonne)[a]	18.0	48.5	48.5	25.0	25.0	25.0	25.0
Harvesting season	June–August	October–March	October–March	Year round	Year round	Year round	Year round
Biomass form	PFF chips	Salix bundles	Salix bundles	Eucal. bundles	Eucal. bundles	Eucal. bundles	Eucal. bundles
LHV (GJ/tonne)[a]	10.0	10.5	10.5	10.7	10.7	10.7	10.7
Moisture content (wt%)[a]	40%	37%	37%	35%	35%	35%	35%
Density (kg/m3)[a]	240	160	160	280	280	280	280
Cost (€2005/GJ LHV)	1.8	4.6	4.6	2.3	2.3	2.3	2.3
Energy used (GJexp/GJprod)	0.0000	0.0045	0.0045	0.0003	0.0003	0.0003	0.0003
GHG (kg $\text{CO}_{2\text{eq}}$/GJprod)[b]	−104	−109	−109	−111	−111	−111	−111
CGP facility scale (tonne/h) [d]	19	26	26	17	17	25	None, immediate processing to FT diesel
Processed at CGP into	Pellets	Pellets	Pellets	Pellets	Pellets	TOPs	
LHV (GJ/tonne)[c]	16.2	16.2	16.2	16.2	16.2	21.6	
Moisture content (wt%)[c]	7%	7%	7%	7%	7%	3%	
Density (kg/m^3)[c]	650	650	650	650	650	800	
Cost (€2005/GJproduct))	1.4	1.1	1.1	0.4	0.4	1.5	
Energy used (GJexp/GJproduct)	0.210	0.167	0.167	0.178	0.178	0.091	
GHG (kg $\text{CO}_{2\text{eq}}$/GJproduct)	38	29	29	31	31	16	
Processed at port into	None	None	FT diesel[d]	None	FT diesel[d]	None	None

[a] Data from Hamelinck [27,34], converted to LHV where needed.
[b] Sum of emissions from primary energy used for production and harvesting and carbon sequestered in the biomass.
[c] Data from Uslu [48].
[d] See text, FT plant are discussed in the next section of this paper.

The properties of the biomass as well as data on most of the equipment are taken from the *Chains* model, as developed for the VIEWLS project [27,28]. For farmed biomass, it is assumed that 30% of the surface area of a given region is used for energy crops. This leaves room for infrastructure, subsistence farming and/or higher value food crops in the same area.

We assume the development of a large market for biomass trade, with a baseline raw biomass cost of 1.9 €/GJ_{LHV} for forestry residues at the side of the road in Canada, 4.9 €/GJ_{LHV} for salix (willow or poplar) at a farm in Eastern Europe and 2.5 €/GJ_{LHV} for eucalyptus at a plantation in Latin America.[7] Initial efforts at market development can use the (limited volume of) biomass residues from agricultural processing that are available at little or no cost.

Preliminary calculations showed that transporting raw biomass is very uneconomic because of its low density.[8] Conversion to FT fuel early in the chain saves on logistics costs but limits the scale of a local FT plant, because feedstock supply is often considered the limiting factor for biomass gasification at a scale of hundreds of MW_{th} and upwards [11].

Conversion of biomass to an intermediate has been the subject of extensive study. Such processing affects the WTW chain by adding costs and energy use and by reducing transportation expenses. Options for biomass collection, intermediate conversion and shipping are explored by our institute (e.g. [27,28,45]) and by others (e.g. [46]). Two processes for producing intermediates are considered here:

- Biomass pellet production entails heating small pieces of wood (downsized to about 10 mm) to around 100 °C, at which point the lignin in the wood softens. By subsequent compression and cooling, a stable intermediate is formed [27]. Biomass pellets have a bulk density of 600–700 kg/m^3, about 2–3 times that of wood chips, and suffer less rotting [27].
- Torrefaction entails heating to moderate temperature (230–270 °C for 10–40 min) to produce a material like charcoal [47]. This material is easily densified into pellets (abbreviated as TOPs) [47,48], which have a bulk density of up to 800 kg/m^3. The downside of torrefaction is that some energy is lost in the conversion process itself.

Use of (flash) pyrolysis to produce an intermediate for shipping is not included in this study because the cost of producing FT fuels by way of pyrolysis oil has been found to be higher than the costs associated with the use of plain or torrefied biomass pellets [28,48,45,47].

Data on the efficiency and cost of equipment for producing intermediates are taken from Batidzirai et al. [45] and Uslu [48]. Costs for biomass storage are assumed to be negligible. Biomass losses during storage periods are not considered because of insufficient data.

Table 1 shows the parameters we use for the biomass farming and intermediate production. We assume that the biomass is harvested from trees which do not require significant agricultural inputs such as fertilisers. Additional carbon sequestration into roots and soil is not taken into account, neither are possible carbon losses from establishing biomass farms, nor emissions of greenhouse gasses that could be involved in the biological cycle such as methane and nitrous oxide.[9]

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[7] Some publications have reported biomass cost per higher heating value (HHV). For comparison, residues cost 0.9 €/GJ_{HHV}, salix costs 2.5 €/GJ_{HHV} and eucalyptus costs 1.3 €/GJ_{HHV}.

[8] Compare the energy density of fresh salix bundles (1.5 $\text{GJ}_{\text{LHV}}/m^3$) and eucalyptus bundles (2.8 $\text{GJ}_{\text{LHV}}/m^3$) with the energy density of pellets (10 $\text{GJ}_{\text{LHV}}/m^3$), TOPs (17 $\text{GJ}_{\text{LHV}}/m^3$) and FT diesel (34 $\text{GJ}_{\text{LHV}}/m^3$).

[9] These emissions are highly uncertain and dependant on circumstances in practice [49–53].

Table 2
Data, cost, energy use and GHG emissions for transport of biomass, intermediates, and FT diesel used in this study.

Biomass supply chains-transport	Canadian FR to pellets to WE	EE salix to pellets to WE	EE salix to local BTL	LA eucalyptus to pellets to WE	LA eucalyptus to local BTL	LA eucalyptus to TOPS to WE	LA eucalyptus to CGP BTL
Time frame	*Present (2005)*	*Future (2020)*					
Trucking distance to CGP (km)[a]	186.9	20.4	20.4	18.7	18.7	23.1	44.2
Cost (€2005/GJ_{moved})	1.7	0.3	0.3	0.2	0.2	0.2	0.3
Energy used (GJ_{exp}/GJ_{moved})	0.0132	0.0017	0.0017	0.0012	0.0012	0.0015	0.0029
GHG (kg CO_{2eq}/GJ_{moved})	1.00	0.13	0.13	0.09	0.09	0.12	0.22
Transport distance to seaport or processing plant (km)[2]	None[b]	300 (Train)	300 (Train)	300 (Push tug)	300 (Push tug)	300 (Push tug)	300 (Class IV tanker)
Cost (€2005/GJ_{moved})		0.4	0.4	0.1	0.1	0.1	0.1
Energy used (GJ_{exp}/GJ_{moved})		0.0030	0.0030	0.0023	0.0023	0.0015	0.0021
GHG (kg CO_{2eq}/GJ_{moved})		0.23	0.23	0.19	0.19	0.12	0.17
FT plant location[c]	Western Europe	Western Europe	Local	Western Europe	Local	Western Europe	Local
Transported by	Bulk carrier	Bulk carrier	Bulk tanker	Bulk carrier	Bulk tanker	Bulk carrier	Bulk tanker
Ocean shipping form[c]	Pellets	Pellets	FT diesel	Pellets	FT diesel	TOPs	FT diesel
Ocean shipping distance (km)	6000	6000	6000	12,000	12,000	12,000	12,000
Cost (€2005/GJ_{moved})	0.2	0.2	0.1	0.2	0.1	0.2	0.1
Energy used (GJ_{exp}/GJ_{moved})	0.0115	0.0115	0.0046	0.0230	0.0091	0.0167	0.0091
GHG (ka CO_{2eq}/GJ_{moved})	0.94	0.94	0.37	1.87	0.74	1.36	0.74

[a] See text.
[b] It is assumed that port facilities for shipping wood internationally are already available at the collection point and these can also be used to ship the pellets.
[c] Derived from data from Smeets [54] and Batidzirai [45]. Ocean shipping assumes Suezmax bulk carriers and tankers.

The annualized investment costs for conversion are calculated using a 10% discount factor and a depreciation period of 10 years. Operation and maintenance cost (O&M) for the process units is 3–40%. The proposed TOPs process has a high degree of heat integration and is therefore extremely efficient (92%, see [47,48]) but the equipment is much more expensive than a conventional dryer for a pellet plant. Besides conversion, only long-range trucking contributes substantially to the cost of biomass chains. Two chains with FT production inside the country of origin, but not in the farming area, use pellets as an intermediate because the extra cost of transporting bundles of wood outweighs the losses from the conversion process.

3.2.3. Logistics of biomass supply

The biomass supply area and collection logistics are scaled to match seasonal availability and the input capacity of the pellet or TOPs plant, optimizing the size of the most expensive component for scale advantages. The following formula is used to determine the average collection distance (derived from [55]):

$$\text{Average Range(km)} = (\mathit{CGP}\ \text{Facility Capacity/Yield per ha}\ /\text{Coverage\%}/\pi^{*}1.3)^{\text{wedge}1/2} \qquad (9)$$

The 1.3 in formula (9) is a factor to correct between the radius to the perimeter of a circular area and the average distance in an area where distance from the centre is counted through roads and other pathways.

Table 2 shows the parameters for the collection of raw biomass to the CGP, subsequent transportation of intermediates and FT diesel to a port facility in the country of origin, and long range shipping to Western Europe.

3.3. Fischer–Tropsch conversion

Production of Fischer–Tropsch fuels requires that the feedstock is gasified and the resulting synthesis gas catalytically converted to hydrocarbons. The process is less efficient but more flexible than biological processing [27] and produces a much higher quality fuel than hydrothermal upgrading [46] or direct coal liquefaction [56]. While only natural gas, coal and biomass are considered here, gasification can be made to work with many different feedstocks, including municipal waste [57].

Fig. 3 depicts a schematic diagram of the structure of the CTL or BTL FT plant used in this study. Note that some elements are depicted in an aggregated fashion. For instance, the gasifier section includes gasification and gas cleaning. The same structure is applied mutatis mutandis to a GTL plant.

In our study, costs are calculated mostly for plants with a capacity of 400 and 2000 $MW_{th\ input}$. For larger plants, scale advantages are less pronounced, because much of the equipment would be installed in parallel sets. 2000 $MW_{th\ input}$ is equal to an output of around 16,000 barrels per day (bpd).[10]

3.3.1. Syngas production

For solid feedstocks (coal and biomass intermediates) three types of gasifiers are used in this study:

- Fluidized Bed gasifiers, which can be scaled to several hundred of MW_{th}. Temperature varies between 700 °C and 1100 °C. This type of gasifier produces considerable amounts of tar and aromatics [60] which makes extensive gas cleaning necessary. Moreover, it accepts a wide variety of feedstocks in large particles (up to 10 cm).
- Entrained Flow (EF) gasifiers, which are typically large units (up to several GW_{th}). The temperature usually exceeds 1300 °C, leading to almost complete conversion of the feedstock to syngas. This type of gasifier requires very small (1 mm diameter maximum) particles and produces inert slag.
- Two-stage gasifiers, such as the Carbo-V® gasifier being developed by CHOREN Industries, combine feedstock flexibility with complete conversion but are also more complex to build [61].

Another option for syngas production is methane reforming. Dry [19] indicates that methane-fed plants are about 30% cheaper to build. There are possibilities to improve the conversion effi-

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[10] By comparison, the typical capacity of a coal power plant is 1000–1600 $MW_{th\ input}$, but two large refineries in the port of Rotterdam each process around 400,000 bpd (Shell corporate website, Exxon-Mobil corporate website). Sasol-Chevron indicate their integrated FT process can process around 15,000 bpd [33]. This will require scaling up of gasifiers, as those used in existing IGCC power plants (Puertollano, Buggenum) are in the range of 700 $MW_{th\ input}$ [58]. The only BTL plant under construction in 2007, CHOREN's Beta plant in Freiberg, has a capacity of around 45 $MW_{th\ input}$ [59].

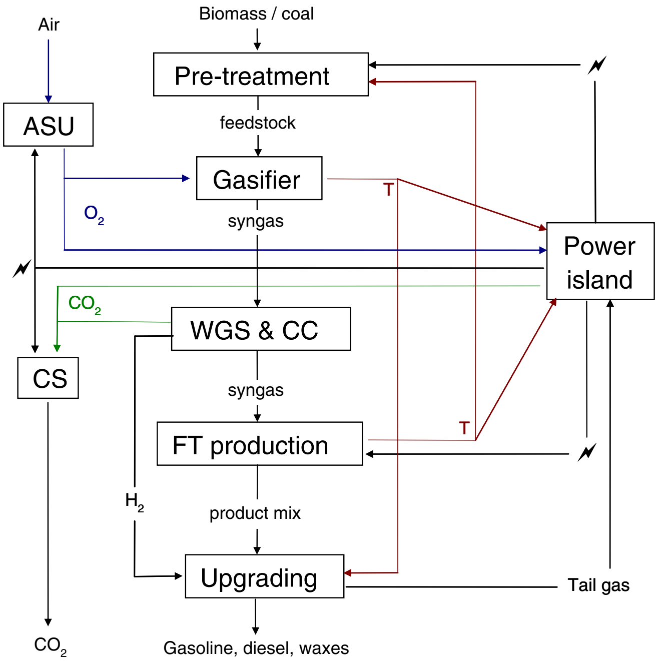

Fig. 3. General layout of an FT plant as used in this study (ASU = air separation unit, WGS = water gas shift, CC = CO_2 capture, CS = CO_2 storage).

ciency of these plants by using catalytic reformers. Even in this configuration, syngas production accounts for around half of the capital costs of a FT fuels plant [62]. Current plants fed with natural gas often use autothermal reformers (ATR) [62–64].

Key parameters for the various gasifiers and reformers used in this study are presented in Table 3:

All gasification systems are oxygen-blown, as previous research has indicated these to have superior performance [70,60] and the presence of nitrogen in the synthesis gas is not desirable. All gasifiers are pressurized (at 20 bar or more) because it allows for a smaller gasifier and the FT synthesis requires a pressurized gas feed anyway [11,14]. The selection of gasifier type ultimately depends on design choices such as scale, feedstock(s) and product mix [71–73].

Little improvement is expected in the efficiency of EF gasifiers [74], which is currently just below 80% for bituminous coal in a Shell EF gasifier [14] or biomass in a CHOREN multistage gasifier [59]. Existing autothermal reformers for natural gas may be replaced by catalytic reformers [62] and model calculations show possibilities for a natural gas conversion efficiency of at least 80% [66].

Gas cleaning facilities are used where required to reach a tar- and sulphur-free synthesis gas. The extent of the facilities depends on the gasifier type: only the fluidized bed gasifier requires tar removal, all except the ATR units need cyclones and dust filters and all plants have guard beds to protect the FT catalyst. A sour water–gas shift unit is included to provide the required H_2/CO ratio and assist in removing sulphur from the syngas. Cost data for the WGS unit are taken from [14], and for all other gas cleaning units from [11].

Advances are expected in gasifier peripherals. New feeding mechanisms [75,76] and dry gas cleaning systems for fluidized bed gasifiers [77] are under development, but these have not yet been deployed on a commercial scale [15]. The model plant based on a bubbling fluidized bed (BFB) gasifier [65] uses a dry gas cleaning system (OLGA from ECN, see [77]).

3.3.2. FT synthesis

In 2007, two Fischer–Tropsch processes had a significant market share: the Shell Middle Distillate Synthesis (SMDS) process and the Sasol Slurry Phase Distillate (SPD) process. Both were developed since the 1980s and have been in commercial use since the 1990s [62,78,65]. SMDS uses a tubular fixed-bed reactor [62]. SPD uses a slurry reactor but a fixed-fluidized bed reactor has also been used [78]. Other processes have been designed by companies such as Syntroleum, but these are not yet applied commercially [79].

The Fischer–Tropsch process has become significantly cheaper and more efficient since it was invented. The most extreme improvement is in reactor design. New plants use low temperature FT processes with values for α[11] of at least 0.92 [19]. Moving from a multitubular to a slurry phase reactor has reduced construction costs, pressure drop and catalyst consumption by ¾, increased conversion and reduced maintenance requirements. On the downside, catalyst poisoning is more damaging in a slurry phase reactor [19], so syngas cleaning must be very reliable.

Upgrading of the FT product is required. In both process designs, a hydrotreating and hydrocracking unit is present to convert waxes to additional fuels [62,78]. For the Shell heavy paraffin conversion (HPC) unit, the output share of diesel fuel was maximised. The diesel fraction has excellent fuel characteristics. The naphtha fraction is further reformed and isomerised to improve the octane number for use as petrol [32,80].

Closer cooperation among producers, or the expiration of patents, may allow competing state of the art techniques to be combined in the future for a 'best of breed' facility. Based on literature descriptions [21,19,62,65] the combination of a Sasol slurry phase reactor, a state of the art FT catalyst, and a Shell heavy paraffin converter unit may provide an optimal combination with regard to production cost, product flexibility and yield. In this study we assume a process of this kind is commercially available by 2020. Key parameters of the three FT processes are summarized in Table 4.

3.3.3. Power island and air separation unit

Synfuels plants include a power island to provide for heat balancing and to generate electricity for both internal use and export. Electricity production is around 10% of LHV input for CTL and BTL plants and around 25% of LHV input for GTL plants. The power island burns the FT tail gas in a gas turbine. The remaining heat, together with the process heat from the gasifier and FT synthesis reactor, is used in a steam cycle. For simplicity, the air separation unit (ASU) and gas turbine are considered as separate units, although integration of the compressors would improve efficiency (see [81]).

ASU data are taken from Bechtel [82].[12] A 5000 tonne/day unit is assumed to cost 178.2 M€$_{2005}$ (scaling factor of 0.7 up to 2045 tonne/day). The energy requirement is 375 kWh/tonne for 94.3% purity oxidant and 390 kWh/tonne for 99.5 purity oxidant.

Unlike in some other studies [60,11], the recycling of FT tail gas to the gasifier (so-called long recycle) is not included in our study, and the tail gas is sent to the power island instead. We choose this approach for three reasons: First of all, the cost per unit of fuel of once-through systems has been shown to be lower [11]. The increased costs for reforming the light components of the FT tail gas exceed the benefits of increased production. According to [14], the difference between once-through operation and recycling of unconverted syngas was calculated to be very small.

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[11] α is a measure of chain growth probability during the FT reaction, and depends on the catalyst used. Higher α produces a mix of heavier hydrocarbons [11]. Heavier mixes are preferred because it is easier to crack heavy hydrocarbon chains than join light ones.

[12] Data cited in [11]. Cost data for ASU varied wildly: between five sources, quoted in [14] and [11], values were found from 54 M€$_{2005}$ to 294 M€$_{2005}$ for the same scale and purity.

Table 3
Main parameters used in this study for syngas production using gasification of coal or biomass, or reforming of natural gas.

Gasifier	IGT BFB	Shell EF		Carbo-V	ATR	
Manufacturer	Institute of Gas Technology	Shell[e]		CHOREN Industries GmbH	None, modelled	
Type	BFB	EF		Two stage (EF)	CPO$_x$[h]	CSR/PO$_x$[h]
Feedstock(s)	Eucalyptus wood	Coal	TOPs[f]	Wood pellets	Natural gas	
Exit temperature (°C)	982	1427	1300	900	900	980
Operating pressure[a] (bar)	34	25	40	25	20	35
Cold gas efficiency[b] (LHV)	76.9%[d]	78.9%	75.0%	78.7%	69.4%	78.3%
Unit cost (400 MW$_{th}$ LHV, M€ 2005)[a]	38	81	129[a,f]	138[g]	45	79
Scaling factor (*R*)	0.7	0.7		0.83[g]	0.7	
Maximum scale (MW$_{th}$)	400	1250		1500	600	
Data source[c]	[65,66]	[14,67,68]		[59,24,14,48]	[65,66,69]	

[a] For different operating pressures of the unit in the source data, we assume unit cost to increase linear with wall thickness, which is assumed to increase linear with pressure [11].

[b] Some carbon mass balances in the source data were incomplete and minor adjustments were made to compensate for this. For cold gas efficiency, this resulted in the parameters presented here.

[c] Data sources provided parameters for syngas composition.

[d] Includes the conversion of methane in a modelled convective methane reformer, using additional oxygen. The LHV efficiency of the gasifier was 80% before reforming. In the untreated product gas, 8.2% of the volume and 44% of the heating value is contained in methane.

[e] Using a GE gasifier for CTL, which is cheaper and less efficient (data from [14]), resulted in a 7% higher fossil energy use over the entire WTW chain and 1% lower fuel costs (due to lower electricity sales). CO_2 crediting slightly increases this difference. Using a different set of gas composition data (simulated by [117], chain-wide fossil energy use was 1–6% lower and fuel costs were 2% lower to 3% higher, depending on the configuration chosen. Larson and Tingjin's data [14] were used because these include simulated as well as experimentally sampled data.

[f] The elemental composition of torrefied wood is very similar to pyrolysis oil. Pyroil data are therefore used for the syngas composition as no data are available about the chemical behaviour of TOPs in an EF gasifier.

[g] As no cost data were available, the two stage gasifier is assumed to be a combined ablative pyrolysis unit [48] and GE gasifier [14]. Parameters reflect the total from both subunits.

[h] Left-side parameters represent a pre-reformer + partial oxidation reformer configuration (CPO$_x$), right-side parameters represent a combined steam reformer + catalytic partial oxidation reactor (CSR-PO$_x$) [66].

Table 4
Parameters for the three Fischer–Tropsch processes used in this study.

FT process	SMDS	SPD	Advanced FT
Process name	Shell middle distillate synthesis	Slurry phase distillate (Sasol)	Slurry phase synthesis + heavy paraffin converter
α (Inferred)	0.94[b]	0.92[b,c]	0.94
H_2/CO ratio (mol/mol)	2.15	2.1	2.1
Operating temperature (°C)	230	230	230
Operating pressure (bar)	40[d]	25.2[e]	30[e]
Syngas conversion (%)	92	92	95
Diesel selectivity[a] (wt%)	85	70	85
Cost	27.0[d]	16.2[d]	19.3
Scaling factor (*R*)	1[d]	0.72[d]	0.72
Reactor size (m^3)	208[d]	362[d]	362

[a] This is the fraction of final product that is diesel fuel after product workup.

[b] From [62].

[c] Evidence has been reported of two different α-values guiding the process in a liquid phase reactor, with the increased value becoming dominant around a carbon chain length of 10 (C_{10+}) [78]. This was not taken into account in this paper.

[d] From [65].

[e] Assumed value, based on [19].

Furthermore, the syngas in that process (DME production) does not require extra reforming. Second, the use (if selected) of carbon capture and storage (CCS) requires significant additional electricity, which is preferably generated on-site. Finally, we assume that excess electricity can readily be sold to the local electrical grid at 38 €/MWh.[13]

3.3.4. Carbon capture and storage

FT fuel plants provide a unique opportunity for carbon capture and storage (CCS). The synthesis gas is stripped of CO_2 during gas cleaning in order to increase the partial pressure of the reactants in the FT section. The resulting stream of almost pure CO_2 from the Selexol unit is readily diverted to carbon storage, if desired [14,87]. About 90–92% of the CO2 in the syngas stream can be removed in this way [88,59]. Most of the remaining carbon is embodied in the FT product.[14] Because CO_2 is removed from the syngas stream to improve FT reactivity, a sizeable flow is available without significant additional costs.

We assume CCS is applied in future FT plants in Europe and Middle East, and not in facilities in Latin America. Following [14], CO_2 drying and compression consume 97.8 kWh per tonne of CO_2 sent to sequestration. A 400 tonne/h unit costs 33.8 M€$_{2005}$ (scaling factor of 0.67). Costs for off-site transport are set at 3.30 €/tonne

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[13] Exported electricity is sold at 38 €/MWh, based on 2005–2006 generation costs and Dutch spot market prices, and 2005–2007 industrial prices in the Netherlands, Belgium, Germany, Poland, Romania, Bulgaria and Brazil [83–85]. Income from electricity exports reduces the FT fuel cost. Also see [86].

[14] Plant CO_2 emissions are reduced by 75% (GTL) to 87–89% (BTL and CTL) using CCS. Oxyfuel combustion could be used in the gas turbine: conversion costs for BTL and CTL are increased by 3–4% and CO_2 emissions are reduced by >99%. Oxyfuel for GTL is not recommended because it requires a much larger ASU to burn an off-gas that largely consists of hydrogen.

Table 5
FT conversion plant configurations used in this study.

	PTL80 SMDS	PTL 400	PTL 2000	PTL 2000 CCS	TTL 2000 CCS	BTL 300 CGP	CTL 400 SPD	CTL 2000	CTL 2000 CCS	GTL 2000 SMDS	GTL 2000	GTL 2000 CCS	XTL 20-80	XTL 50-50 CCS
Feedstock material	FR pellets	Wood pellets	Eucalyp. pellets	Salix pellets	TOPS	Eucalyp. chips	Bituminous coal			ME natural gas			Coal and pellets	Coal and TOPS
Gasifier type[a]	Carbo-V	Carbo-V	Carbo-V	Carbo-V	Shell EF	IGTBFB	Shell EF	Shell EF	Shell EF	PR/SMR	CPO_x	CPO_x	Shell EF Carbo-V	Shell EF
Fischer–Tropsch process[b]	SMDS	Adv. FT	Adv. FT	Adv. FT	Adv. FT	Adv. FT	SPD	Adv. FT	Adv. FT	SMDS	Adv. FT	Adv. FT	Adv. FT	Adv. FT
CCS	No	No	No	Yes	Yes	No	No	No	Yes	No	No	Yes	No	Yes
Scale (MWth in)[c]	80	400	2000	2000	2000	300	400	2000	2000	2000	2000	2000	1595 400	1017 1015

[a] See Table 3.
[b] See Table 4.
[c] The XTL 20-80 plant is scaled to produce the same amount of FT fuel as the CTL 2000, while generating 400 MWth with a biomass gasifier. The XTL 50-50 plant is scaled to produce the same output as the CTL 2000 CCS, but uses TOPS for half the feedstock of the EF gasifier.

and storage at 2.41 €/tonne.[15] We assume a base CO_2 price of 15 €/tonne.

3.3.5. Mixed feedstocks

In order to increase flexibility, it would be desirable to have a single FT plant be able to use different feedstocks, particularly coal (being relatively cheap) and biomass (being CO_2 neutral). Two options for such integration are available. The first option is to have two separate gasifiers and merge the two syngas flows after gas cleaning (see also [90]). The second option is to feed pre-treated biomass such as TOPS, which is much like coal in physical properties, together with coal in the same EF gasifier. Both options will be explored here, each based on a coal-fed plant with a share of its feedstock replaced by biomass. The mixed plants are indicated as XTL plants in the remainder of this paper.

3.3.6. Configurations

Table 5 shows the most important choices made in this study for configuring the Fischer–Tropsch plants.

We assume that conversion to FT develops as follows: The 2005 FT plants are all based on existing plants; the 400 MW CTL plant resembles a Sasol plant (albeit with an EF gasifier), the 2000 MW GTL SMDS plant resembles the Shell Bintulu plant and the pellet fired 80 MW BTL plant resembles CHOREN's demonstration plant. By 2020, it is assumed that new synfuels plants are scaled up by an order of magnitude and use the most promising FT and upgrading processes in development today. We also included more advanced options, where CCS is used in plants located in current Annex B countries [91] and biomass-fired plants attain the same scale as coal or natural-gas based ones.

Estimates of various characteristics of the FT synfuels plants are included in Table 6. The annualized investment costs are calculated using a 10% discount factor and a depreciation period of 10 years. Location factors (see [70], to compensate for differences in labour costs, equipment costs and infrastructure, are not taken into account. Labour and fixed costs of 2000 €/$MW_{th\ input}$ are assumed in addition to 4% O&M. With these assumptions, a BTL FT refinery with a capacity of 100.000 bpd would cost seven billion Euros.

Oil refineries emit 4–9 g CO_{2eq}/MJ of diesel fuel produced [55,6]. The FT plants investigated in this paper emit more. At >80 g CO_{2eq}/MJ, the carbon emissions from a coal-fed FT plant are an order of magnitude higher than from a baseline oil refinery. The same goes for BTL plants, but in this case the carbon was removed from the atmosphere before. GTL plants have lower emissions than coal or biomass based plants, but significantly more than oil refineries.

When CCS is used, all plants have similar and much reduced (9–15 g CO_2/MJ) emissions. The electricity requirement is 1–7% of plant energy input ($MW_e/MW_{th\ input}$), which reduces the available electricity for export. This is lower than for IGCC coal power stations, where near-total CCS is expected to carry an energy penalty of 11% [92] to 14% or more [89]. The break-even price of CO_2 at the plant gate for CCS was calculated to be about €6 per tonne.

Fig. 4 shows a breakdown of TCI. As expected, the gasification section (gasifier and ASU) is the most expensive part of a synfuels plant, followed by the power island. Both are largely mature technologies, and costs reductions per unit of fuel for later plants are mostly caused by scaling factors used in calculating equipment cost for larger plants. If the biomass is not converted upstream into an intermediate, the pre-treatment unit costs about one fifth of the total plant.

3.4. Distribution and driving

Fischer–Tropsch fuels may be distributed pure, or blended with conventional diesel to improve fuel characteristics. In all cases, the distribution infrastructure is identical to the existing diesel network, e.g. ships for long distances and pipelines and trucks for end-point distribution.

While vehicles do not need to be adapted to run on FT diesel, fuel economy and GHG emissions are slightly different. Driving our existing vehicle fleet on (blends of) FT diesel will provide significant benefits to local air quality [93]. The emission reductions are listed in Table 7. At the same time, the combination of hybrid technology and more efficient internal combustion engines [94] can reduce fuel consumption further.

To allow an easy comparison of WTW chains, we assume that vehicles with different drive trains are identical in terms of safety features and amenities. The only difference in performance and weight is that the drive train parts are replaced in the different configurations[16] [10].

Pursuant to Weiss et al. [13], we assume the vehicle is driven 20,000 km per year. The vehicle retail price is annualized using an 8 year depreciation period and 5% discount rate. Maintenance and insurance costs are not taken into account, and are assumed to be the same for all vehicles. Retail prices listed in Table 8 do

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[15] From IPCC [89]. Transport data is from Section 4.6. We assume a 250 km pipeline carrying 4–5 Mtonne/year, mostly on-shore. Storage data is from Section 5.9. We assume a mix of on-shore aquifers, on-shore gas fields and off-shore gas fields.

[16] Some authors have discussed options to reduce vehicle mass [13,96], but others [10,12] have not. By contrast, real world cars have seen a substantial increase in mass over the last decades (see for example, [95]).

Table 6
Calculated properties of the conversion plants investigated in this study.

	PTL 80 SMDS	PTL 400	PTL 2000	PTL 2000 CCS	TTL 2000 CCS	BTL 300 CGP	CTL 400 SPD	CTL 2000	CTL 2000 CCS	GTL 2000 SMDS	GTL 2000	GTL 2000 CCS	XTL 20-80	XTL 5O-5O CCS
Feed volume (tonne/day)	0.46	2.30	11.51	11.51	8.00	2.22	1.37	6.87	6.87	3.45	3.45	3.45	6.22 1.56	3.78 3.77
Feed2fuel energy conversion (%)[a]	49	51	51	51	50	52	49	52	52	31[b]	39[b]	39[b]	51	51
Diesel output (b/d)	554	2854	14,268	14,268	13,659	2136	2189	14,098	14,098	8429	10,723	10,723	14,098	14,098
Electricity exported (MW_e)	5	27	133	89	148	22	39	144	109	447	422	408	142	123
Total capital req. (M€ 2005)	135	390	1398	1436	1351	273	423	1370	1403	1221	1143	1161	1411	1475
Fuel conversion cost (€/GJ)	23	12	8	8	8	11	14	8	8	7	5	5	9	8
Feed/product (kg/kg)	5.02	4.89	4.89	5.09	3.49	6.26	2.95	2.93	3.02	1.62	1.43	1.45	3.32	3.28
Energy expended (MJ_{ex}/MJ)[a]	0.71	0.70	0.66	0.77	0.63	0.52	0.56	0.63	0.67	1.03	0.65	0.68	0.64	0.67
Diesel share in fuel output (%)	85	85	85	85	85	85	70	85	85	85	85	85	85	85
CO_2 emissions (g/MJ)	122	116	136	15	11	122	88	86	11	38	17	5	92	11
CO_2 captured (g/MJ)	0	0	0	121	75	0	0	0	80	0	0	14	0	79

[a] The apparent disparity between feed2fuel conversion and energy expended is a result of crediting for avoided stand-alone electricity generation.
[b] Methane reforming produces an excess (+50%) of hydrogen, which is used to generate additional electricity.

not include VAT, but may include some other taxes, including license and registration.

$$\text{Vehicle Cost } (€/\text{km}) = \text{Retail Price} * \text{DR}\%/(1-(\text{DR}\%+1) - \text{Lifetime}/20,000\,\text{km per year} \qquad (10)$$

We use the fuel distribution and vehicle data developed by the EU's Joint Research Centre [10]. This data has been gathered in cooperation with major EU car manufacturers and the results are appropriate for European situations[17] and driving cycles. The fuel consumption and emissions used in this study were determined using the New European Driving Cycle (NEDC) for a 'median EU vehicle' (resembling a VW Golf). The widely used ADVISOR model from NREL was adapted to the EU situation for this purpose.

The 2002 vehicles from the JRC study are selected as representative for 2005 and a 2010 hybrid vehicle was selected to represent the average car in 2020. Table 8 shows the configurations of for both fossil diesel and FT driven cars. The fossil and FT pairs are largely identical except that cars fuelled with FT diesel emit around 3% less carbon. We assume a somewhat conservative 20% reduction in future fuel consumption: a reduction of around 25% is indicated by SRU [9].

We assume that drive train adoption develops as follows: Internal combustion engines will generally get better in the next 15 years, leading to more fuel-efficient cars. Hybrid cars, which achieve significant higher fuel economy, achieve a dominant market share. Some of the efficiency gains are negated by further increases in the weight of cars. All future cars are equipped with diesel particulate filters (DPF) to reduce air pollution.

4. Results

An overview of the various WTW chains that are investigated for this paper can be found in Table 9. The chains are a limited selection from the literally thousands of individual chains that could be defined (if considered in sufficient detail) and are intended to showcase what the authors consider reasonable developments in Fischer–Tropsch fuel production.

The results over the entire WTW chains can be found below in Table 10 and the comparative Figs. 5, 7 and 9. Note that the calculated costs are not the same as prices paid by the consumer. VAT and various taxes are **not** included in the calculation and increase the effective cost of driving.

4.1. Well-to-wheel energy use

The results show that total energy use will not be reduced by switching to Fischer–Tropsch diesel. A breakdown of contributions to total energy use in each chain is presented in Fig. 6.

It is observed from Fig. 6 that the most constant difference between total energy use in fossil diesel chains and FT diesel chains stems from losses in the conversion plants. Of the total WTW energy, just under 50% (for CTL- and BTL-based chains) to a maximum of 87% (for crude oil chains) is used in the vehicle.

Fossil energy is used in biomass chains for transport and farming, but this is a minor share of the total energy consumption and less than the energy use in the reference chains. The worst case pure biomass-based chain uses around 5% of the fossil energy of the most optimal fossil-based chain, not taking uncertainty in the data into account. In the best case for biomass, the fossil energy requirement (FER) is around 1% of that of a coal-based chain.

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[17] Most WTW studies use US vehicles (with the average car resembling a Toyota Camry) and driving cycles.

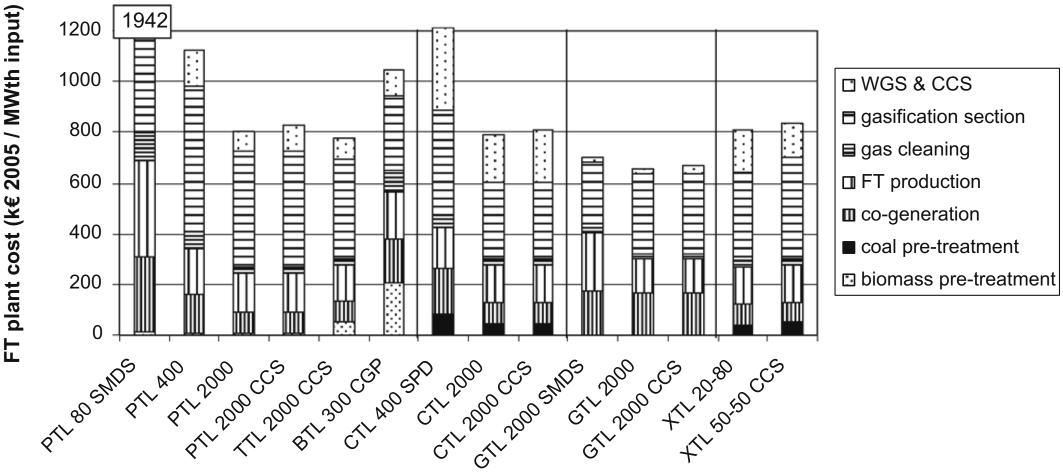

Fig. 4. TCI breakdown of the conversion plants investigated in this study.

Table 7
Emission reductions with a standard VW Golf using Shell GTL diesel instead of fossil diesel. Source: [95,93].

	NO_x	PM_{10}	Hydrocarbons	CO
FT vs. fossil (%)	−6.4	−26 to −28	−63	−91

4.2. Well-to-wheel cost

The median fuel cost for FT and fossil diesel chains is around €0.02 per km. Important in this respect is that 83–95% of the total costs per km can be attributed to the vehicle, which somewhat levels out the differences between the various fuel production methods. To facilitate a comparison between the well-to-tank parts of the chain, a breakdown of the cost per litre of fuel is given in Fig. 8.

With feedstock and transport costs as assumed, diesel from crude oil could be delivered at around € 0.41 per litre. FT diesel costs may range from just over half that number (using low feed prices and high efficiency conversion plants) to almost twice as much (using inefficient biomass-based processes).

Using natural gas at a cost equivalent to production prices (1.07 €/GJ_{LHV}, see Section 3.2.1) would make GTL the cheapest option in the medium and long term (due to electricity revenue). The corresponding break-even (vs. fossil diesel) oil price is found to be 36 $/bbl, which would account for the enthusiasm with which oil companies are investing in GTL plants in recent years.

At the assumed fossil fuel prices and biomass feedstock prices (2.5 €/GJ_{LHV} for Eastern Europe and 4.9 €/GJ_{LHV} for Latin America) BTL is more expensive than all other FT options. The break-even oil price for BTL is above 75 $/bbl. The break-even oil price for CTL is found to be 60 $/bbl and mixed biomass-with-coal chains will end up somewhere in this range. Break-even oil prices between 45 $/bbl and 70 $/bbl were presented for CTL and XTL plants by Williams et al. [90].

The results indicate that FT diesel will be competitive when made from very cheap feedstocks or when oil prices stay above 75 $/bbl. The most constant difference between the costs of fossil diesel and FT diesel stems from the cost of conversion plants. The FT plants are consistently (much) more expensive per unit of fuel than oil refineries, a condition that is obviated by lower feedstock costs only if feedstocks are extremely cheap (because more feedstock is needed with feed-to-fuel efficiency around 50%).

4.3. Well-to-wheel greenhouse gas emissions

Fig. 9 demonstrates that the use of CTL and GTL fuels will not necessarily reduce GHG emissions. In the case of CTL without CCS, GHG emissions would increase by 110% over those from fossil diesel chains. Even with CCS, emissions from CTL chains are found to be 25% higher, owing mostly to GHG emissions from mining. Without CCS, even GTL is found to cause up to 10% higher GHG emissions than fossil diesel. In the future, highly efficient conversion plants with CCS could give GTL a slight advantage over and oil-derived fuels (compare reference path B with FT path 9), reducing emissions by 5% vs. fossil diesel, though this reduction is largely due to GHG credited from electricity exports.

The GHG emissions from BTL chains all appear to be much lower than those of fossil diesel, many reducing GHG emissions by around 75% (assuming here that biomass feedstock is produced in a GHG neutral way). If CCS is combined with BTL, a net reduction of atmospheric CO_2 is achieved, making for climate-positive driv-

Table 8
Vehicle parameters used in this study.

Vehicle data	Current drive train		Improved engine hybrid	
Year	Present (2005)		Future (2020)	
Fuel type	Fossil	FT	Fossil	FT
Particulate filter?	No	No	Yes	yes
Retail price	20,300	20,300	27,590	27,590
Cost (€2005/km)	0.16	0.16	0.21	0.21
Cost uncertainty			0% to +15%	0% to +15%
Energy required (MJ/km)	1.83	1.83	1.46	1.46
energy uncertainty	−3% to +3%	−3% to +3%	−10% to +8%	−10% to +8%
GHG em. (CO_{2eq}/km)	138	133	108	105
Engine configuration (kW ICE + electric)	74	74	74 + 14	74 + 14
Fuel economy vs. current generation	–	–	−20%	−20%

Table 9
Summary of the properties of the 17 WTW chains investigated in this study.

Nr.	Source	Source transportation	Source conversion	Long range transportation	Destination conversion	Vehicle	Gasifier type	FT process	CCS?	Scale (MW)	Remark
2005 Chains (present)											
1	Middle East natural gas	Pipeline (short distance)	GTL plant	Fuel tanker (12,000 km)	None	Current drive train	ATR	SMDS	No	2000	FT fuel exists within the niche markets where it emerged. It is used primarily as a compatible substitute with desirable characteristics.
2	Bituminous coal	Chains steps included in the source data			CTL plant		Shell EF	Sasol SPD		400	
3	Canadian FR	Truck (187 km average)	Compression to pellets	Ocean bulk carrier (6000 km)	BTL plant		Carbo-V	SMDS		80	
2020 Chains (future)											
4	Middle East natural gas	Pipeline (short distance)	GTL plant	Fuel tanker (12,000 km)	None	Improved engine hybrid	Cat. ATR	SPMDS (Sasol SPD synthesis with Shell HPC upgrading)	No	2000	FT fuel has a significant share of the automotive fuel market. Gasification technology and CCS have not developed to potential. BTL plants are located in Western Europe
5	Bituminous coal	Chains steps included in the source data			CTL plant		Shell EF				
6	Eastern Europe Salix	Truck (20 km average)	compression to pellets	train (300 km) and bulk carrier (6000 km)	BTL plant		Carbo-V			400	
7	Latin America Eucalyptus	Truck (18 km average)	compression to pellets	IWW (300 km) and ocean bulk carrier (12,000 km)							
8	Bituminous coal, Eastern Europe Salix	Coal: chains steps included in the source data biomass: chain steps equal to chain 6			XTL plant		Shell EF and Carbo-V			1595 400	
9	Middle East natural gas	Pipeline (short distance)	GTL plant	Fuel tanker (12,000 km)	None		Cat. ATR		Yes	2000	FT fuel has a significant share of the automotive fuel market. Biomass gasification technology has made improvements in scale and gas cleaning. CCS entered general use in Europe. BTL plants are also located in source regions.
10	Bituminous coal	Chains steps included in the source data			CTL plant		Shell EF				
11	Eastern Europe Salix	Truck (20 km) and train (300 km)	BTL plant	fuel tanker (6000 km)	None		Carbo-V				
12	Latin America Eucalyptus	Truck (23 km average)	conversion to TOPS	IWW (300 km) and ocean bulk carrier (12,000 km)	BTL plant		Shell EF				
13		Truck (18 km) and ship (300 km)	BTL plant	fuel tanker (12,000 km)	None		Carbo-V		No		
14		Truck (44 km average)		IWW (300 km) and ocean fuel tanker (12,000 km)			BFB			300	
15	Bituminous coal, LA Eucalypt.	Coal: chains steps included in the source data biomass: chain steps equal to chain 12			XTL plant		Shell EF		Yes	1017 1015	
Reference chains											
A	Crude oil (at 8.17€/GJ)	Pipeline (short distance)	None	Fuel tanker (12,000 km)	Refinery	Current drive train	Not applicable, assuming current practice				Crude oil prices are equivalent to a $50.62/bbl price in 2005 (IEA, 2006).
B	Crude oil (at 8.17€/GJ)					Improved engine hybrid					

Note: All distribution inside the EU is done with fuel trucks.

Table 10
Summary of WTW chain results for FT and crude oil-based diesel.

Nr.	Source	Conversion and transport	Vehicle	Fossil energy used (MJ/km)	Cost of fuel (€2005/l)	Cost of fuel (C2005/GJ)	Break-even oil price ($2005/bbl)	Cost of driving (€/km)	GHG emissions (g CO_{2eq}/km)	Cost of avoided CO_2
2005 Chains (present)										
1	Middle East natural gas	Converted at source, shipped as fuel	Current drive train	3.89	0.31	9.1	47	0.17	220	n/a
2	Bituminous coal	Shipped as coal, converted at destination		3.17	0.58	16.9	88	0.19	343	n/a
3	Canadian FR	Shipped as pellets, converted at destination		0.09	1.12	32.7	170	0.22	90	535
2020 Chains (future)										
4	Middle East natural gas	Converted at source, shipped as fuel	Improved engine hybrid	2.52	0.23	6.8	36	0.22	141	n/a
5	Bituminous coal	Shipped as coal, converted at destination		2.63	0.40	11.5	60	0.23	270	n/a
6	Eastern Europe Salix	Shipped as pellets, converted at destination		0.05	0.85	24.8	129	0.25	36	211
7	Latin America Eucalyptus			0.07	0.64	18.5	96	0.24	32	107
8	Bituminous coal, Eastern Europe Salix	Shipped as coal and pellets, converted at destination		2.13	0.47	13.6	71	0.23	225	n/a
9	Middle East natural gas	Converted at source, shipped as fuel		2.56	0.23	6.8	36	0.22	123	2.56
10	Bituminous coal	Shipped as coal, converted at destination		2.70	0.39	11.4	60	0.23	161	n/a
11	Eastern Europe Salix	Converted at source, shipped as fuel		0.03	0.70	20.4	106	0.24	−126	52
12	Latin America Eucalyptus	Shipped as TOPS, converted at destination		0.05	0.51	14.9	78	0.24	−129	20
13		Converted at source, shipped as fuel		0.02	0.49	14.2	74	0.23	63	60
14		Converted at CGP, shipped as fuel		0.02	0.53	15.5	81	0.24	39	66
15	Bituminous coal, LA Eucalypt.	Shipped as coal and TOPS, converted at destination		1.37	0.47	13.8	72	0.23	13	30
Reference chains										
A	Crude oil (at 8.17 €/GJ)	Shipped as crude oil, refined at destination	Current drive train	2.11	0.41	11.5	63	0.18	164	n/a
B	Crude oil (at 8.17 €/GJ)		Improved engine hybrid	1.68	0.41	11.5	63	0.23	129	n/a

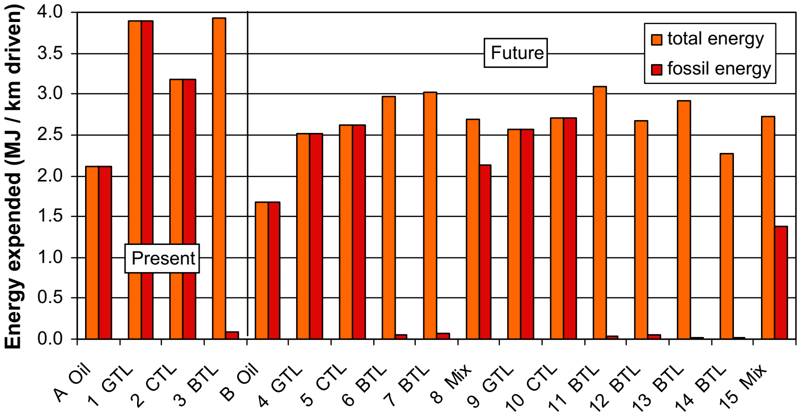

Fig. 5. Total and fossil energy use per km driven in the selected WTW chains.

ing. This effect can be used to compensate for the emissions of fossil feedstocks: when using a mix of 54% biomass and 46% coal in our advanced XTL plant, total chain emissions are zero. When mixing either BTL-CCS chain with fossil diesel, the required share of BTL would be 50%.

4.4. Supply chain issues

Fig. 10 shows the difference between profiles for energy and costs to supply biomass to FT plants (field-to-gate). In all cases, conversion to an intermediate (pellets or TOPS) causes by far the

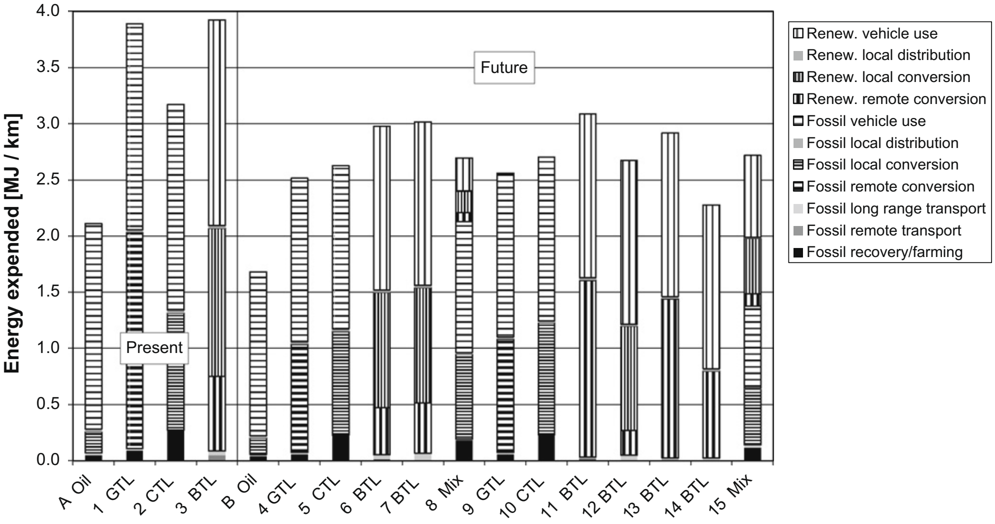

Fig. 6. Breakdown of total energy expended per km driven for each selected WTW chain.

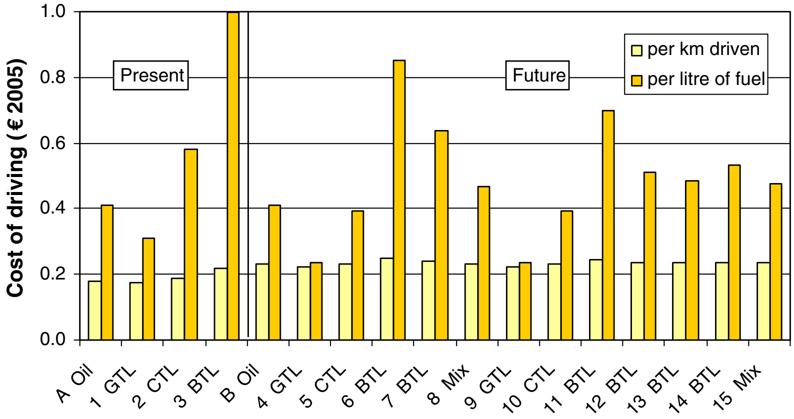

Fig. 7. Costs per km driven and per litre for each selected WTW chain.

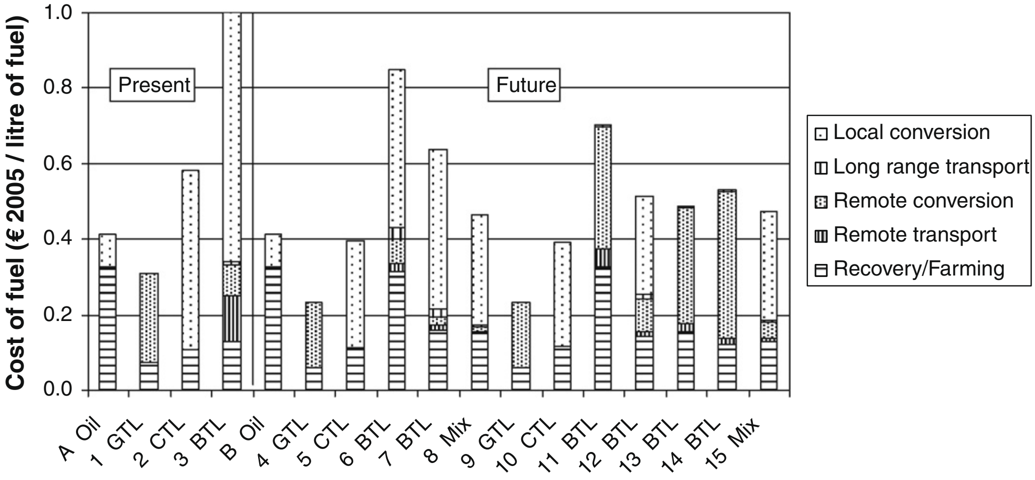

Fig. 8. Breakdown of fuel cost per litre in individual chain links in WTT chains.

most energy loss, but the biomass feedstock is the most costly element. Costs and energy expended for collecting the biomass are important only in chain 3, where long distances must be covered by truck to collect forestry residues. Long range transport has a

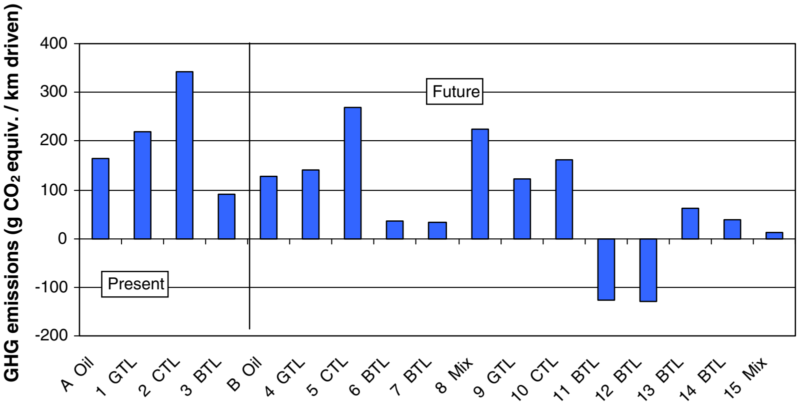

Fig. 9. GHG emissions per km driven for each selected WTW chain.

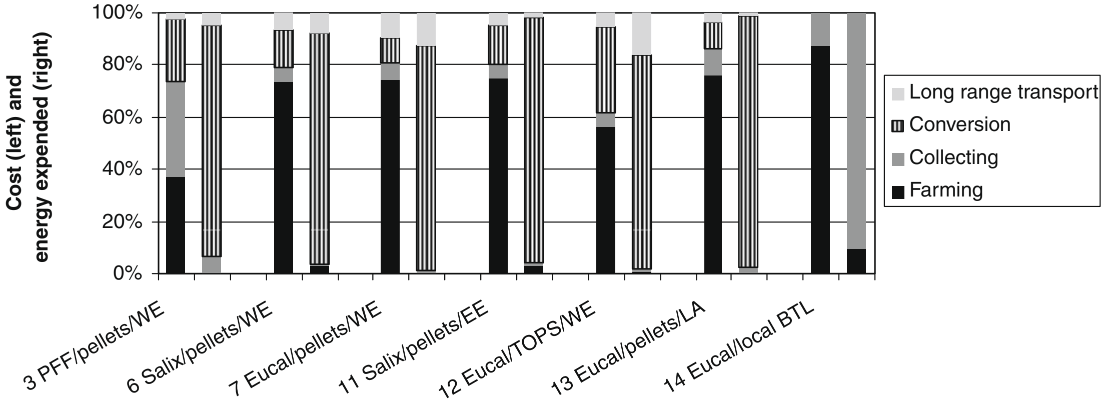

Fig. 10. Shares of total cost and energy expenditure of biomass supply chains up to the factory gate.

minor role in both energy and cost even when intermediates need to be shipped over 12,000 km.

Despite its minor role in total costs and emissions, the long range transport of Fischer–Tropsch feedstocks could have a large impact on logistical centres because the volume of FT feedstock that must be processed upstream is much larger than the volume of oil required for the same amount of fuel. Compared to fossil diesel, about 2.9 times the volume of feedstock is needed to produce CTL. For BTL from TOPs, this is 3.4 times and for BTL from wood pellets, the volume rises to 6.1 times the volume of crude oil. Replacing fossil diesel with FT diesel could therefore require an extension of port facilities. GTL and BTL chains that convert to FT in the region of origin would require extensions to port facilities only in their respective regions.

It is also evident that the collection of raw biomass will require a large logistical operation. Using available point sources of agricultural residues can save cost and energy (see Fig. 11).

4.5. Sensitivity

To determine which parameters have a significant effect on the results, sensitivity analysis was done for changes in feedstock costs, price of primary diesel and heavy fuel oil for transportation, FT α, oil and electricity price, CO_2 credit price and discount rate. Effects of carbon leakage, caused by methods of obtaining biomass that have significant emissions of GHG as well as sequestration effects, are also investigated. Ranges for oil, gas and coal price variations were obtained from the World Energy Outlook 2006 and 2007 [86,17]. The sensitivity for transport fuel cost and FT α was found to be negligible. Indicative results are presented in Fig. 12.

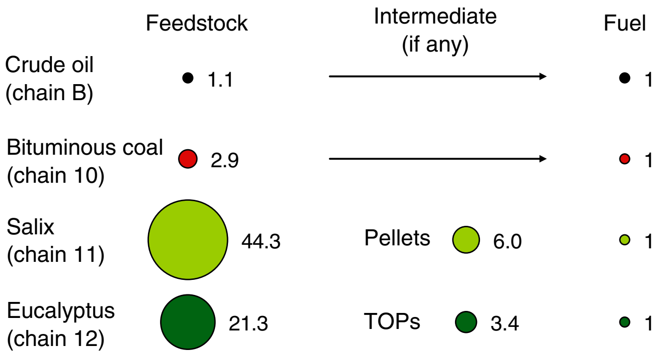

Fig. 11. Relative transported volumes of raw feedstocks and intermediates.

The cost of fuel and the cost of avoided GHG emissions are most sensitive to equipment costs. We estimate equipment costs to range between −20% and +200% or more, which highlights the influence of this factor. At the same time, viability of FT diesel strongly depends on the volatile price of the oil it is to replace (see Fig. 13).

For BTL, the biomass feedstock cost is an influential determinant of FT diesel cost. For most chains, doubling or halving the feedstock cost would entail a rise or fall of fuel costs by 20–40%. The difference between 4.9 €/GJ_{LHV} base price for salix and 1.9 €/GJ_{LHV} base price for eucalyptus shows that such variations are easily possible. Supply curves made in the VIEWLS project of the European Commission indicate that the marginal cost of feedstock from

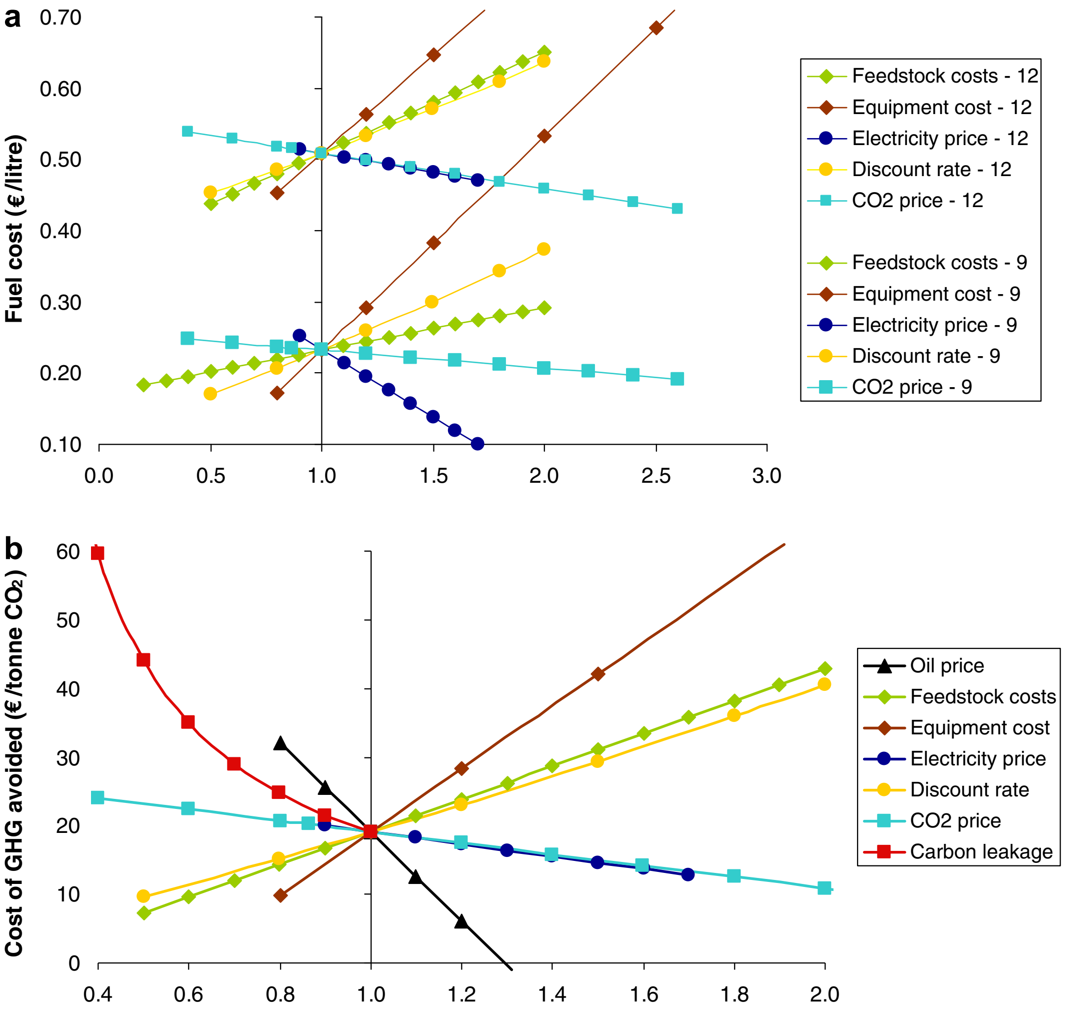

Fig. 12. (a) Sensitivity of FT diesel cost of GTL CCS (9) and BTL LA TOPs CCS (12) chains. (b) Sensitivity of cost of avoided GHG emissions of the LA BTL TOPs CCS (17) chain.

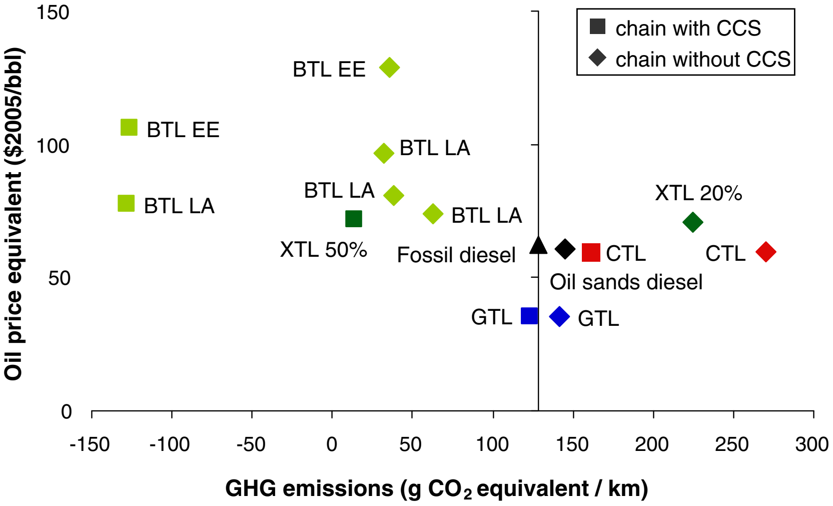

Fig. 13. Cost of fuel in oil price equivalent vs. carbon emissions per km driven as found in this study.

Eastern Europe could range between approximately 2–20 €/GJ_{LHV}, depending on the quantities required [41].

In case of non-trivial carbon leakage, the GHG benefits of BTL quickly disappear. The biomass-based chains without CCS produce more GHG emissions than fossil diesel chains when around 20–25% of the sequestration by plants is negated. The chains with CCS reduce GHG emissions compared to fossil diesel chains when up to 70% of the carbon sequestration from plants is lost.

Table 11
Comparison with FT plant characteristics from [90,97,98,65,11].

Source	Fuel cost (€/GJ)[a]	GHG emitted (g CO_2/MJ)	Feed-to-fuel efficiency (%)	Configuration
Oil baseline	15	88	91	Baseline refinery
GTL, as in chain 9	8	84	39	2000 MW, catalytic POx reformer, with CCS
CTL, as in chain 10	13	110	52	2000 MW, Shell EF, with CCS
CTL, Williams et al. [90]	12	29	33[b]	C-FT-C: CTL, entrained flow gasifier, with CCS
CTL, Gray and Tomlinson [97]	6	100	HHV: 56	Tailgas less CO_2: CTL, unknown gasifier, with CCS in FT tail gas, uses iron-based FT catalyst
BTL, as in chain 6	29	25	44	400 MW, Carbo-V, pellet intermediates shipped to WE, no CCS
BTL, as in chain 11	24	−87	48	2000 MW, Carbo-V, pellet intermediates converted in EE, with CCS
BTL, as in chain 12	18	−88	46	2000 MW, Carbo-V, TOPs intermediates shipped to WE, with CCS
BTL, as in chain 14	18	27	52	300 MW, BFB gasifier, raw biomass converted at CGP, no CCS
BTL, Küpers et al. [98]	41	79	Not listed	BIG-FiT: CFB gasifier, no CCS
BTL, Tijmensen et al. [65]	16 → 11 (long term)	n/a	44–49	BTL, 367 MW$_{th}$ fluidized bed gasifier, no CCS
BTL, Hamelinck et al. [11]	15	n/a	46	BTL, 400 MW$_{th,HHV}$ fluidized bed gasifier, dry gas cleaning, 60 bar FT, no CCS
BTL, Hamelinck et al. [11]	16	n/a	45	BTL, 400 MW$_{th,HHV}$ fluidized bed gasifier, wet gas cleaning, 60 bar FT, with CCS
XTL, as in chain 8	16	155	50	Uses 20% biomass, separate Shell EF gasifier using coal, and Carbo-V gasifier using pellets, no CCS
XTL, as in chain 15	16	9	49	Uses 50% biomass, single Shell EF gasifier using coal and TOPs intermediaries, with CCS
Williams et al. [90]	10	24	32[b]	C/B-FT-CoC: uses 28% biomass, XTL, separate EF gasifier using coal and FB gasifier using switchgrass, with CCS

[a] Includes feedstock, not adjusted tor inflation.
[b] Both Williams' plants have a large electricity co-generation share: 430 MWe and 460 MWe, respectively, for a 1032 MW FT plant. This choice leads to a lower feed-to-fuel efficiency.

Using a 10% discount rate for FT plants in the baseline analysis is something of a compromise. For government policy, a 5% rate is often proposed, while a discount rate of 20% or higher would more accurately reflect the preference for a short payback time in the oil industry. The effect of a 20% discount rate for most chains is an increase of the cost of FT diesel by 13–18 €ct/l and the effect of a 5% discount rate is a decrease of 5–8 €ct/l.

The effect of variation in electricity prices on FT diesel cost is small: a decrease of at most 4 €ct/l for an increase to 55 €/MWh, except for the GTL chains (having more co-generation) which show a decrease of up to 15 €ct/l.

The cost of FT diesel is not very sensitive to the CO_2 price. When comparing no CO_2 credits to a base CO_2 credit price of 14 €/tonne, fuel costs are reduced by 1 to 3 €ct/l (this includes additional expenses for transportation and storage). If CO_2 price doubles, the cost of BTL diesel would drop by another 3–6 €ct/l or around 10%.

5. Discussion

In this section, our result is compared to results from other authors, and several issues are brought forward that emerged during the preceding analysis.

5.1. Comparison of FT plants to literature

When compared to data from literature, the efficiency of the FT plants listed in Table 6 is in the 50–55% range accounted for by Bakhtiari [20]. Our conversion costs are in the same range and our fuel-to-feed efficiency is somewhat higher than what other authors have found. Results from some well-known studies are listed in Table 11 for comparison.

At 650–850 €/KW$_{th\ input}$, the plants calculated here are substantially cheaper than earlier estimates for small scale biomass-fed power plants (see for example [99]. At the same time it is quite difficult to compare conversion plants from literature sources because of the diversity in configurations, assumptions and technologies used. Moreover, not all studies include detailed cost analysis (see for example [100]).

5.2. Comparison of well-to-wheel alternatives with literature

A comparison of selected WTW chain results with other studies[18] can be found in Table 12.

Our results are quite similar to the results obtained by Edwards et al. [10], with the exception of the GHG emissions for biomass, which is probably caused by different assumptions in accounting for these emissions.

We found a fossil energy requirement of BTL in the long term to be 1% to 3%, almost all of which is oil-based. This percentage is lower than the FER of sugarcane ethanol from Brazil of around 10%, [101]. It also contrasts to the FER of US corn-based ethanol production, which is said to be in the range of 20–100% [101,102].

5.3. Uncertainty

The results presented in this paper are based on publicly available data. These data were extrapolated where necessary and feasible. It should be noted that significant uncertainties surround many of the numbers involved. Important sources of uncertainty are listed in Table 13. A 'low' impact does not lead to significant changes in our conclusions. A 'medium' impact denotes something that is noticeable in cost or in GHG emissions but makes a given WTW chain only moderately less favourable (around 4 €ct/l difference for diesel costs), but the general conclusions of the previous sections still hold. A 'high' impact has the potential to invalidate major conclusions about that particular chain. Most of the causes of uncertainty are independent of each other and the effects stack rather than mitigate each other. The uncertainties also appear to have non-Gaussian, flat (possibly uniform) distributions.

Other authors [6,10] have reported ranges of uncertainty of the same order of magnitude. In addition to the uncertainties inherited from the data, we used an Excel-based model and results may differ from those reached in more detailed studies that use Aspen

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[18] Most WTW studies use U.S. driving cycles, which are similar but not fully compatible with the NEDC.

Table 12
Comparison of selected WTW chains with chains from literature [6,10] on energy use, GHG emissions and cost of GHG avoided.

Fuel production technology[a]	Source	Total energy (MJ/100 km)[b]	Fossil energy (MJ/100 km)[b]	GHG Emissions [g CO_{2eq}/km)[b]	Fossil energy requirement (%)	Cost of GHG avoided (€/tonne)
Conventional diesel (COD1)	Edwards et al. [10]	205–219	205–219	158–170	100	n/a, baseline case
Conventional diesel	Hendriks et al. [6]	180–300	180–300	132–219	100	n/a, baseline case
Biodiesel, REE with glycerine as animal feed (ROFE2)	Edwards et al. [10]	390–439	66–85	42–112	18	110
BTL, ex farmed wood (WFSD1)	Edwards et al. [10]	374–426	6–18	13–26	3	188
BTL, ex EE salix (chain 6 WTT)	This study	374	7	46	2	210
BTL, ex LA eucal. (chain 7 WTT)	This study	379	9	41	2	107
CTL(KOSDI)	Edwards et al. [10]	340–382	340–382	346–392	100	n/a, +125% emissions
CTL, no CCS (chain 5 WTT)	This study	330	330	341	100	n/a, +108% emissions
CTL, with CCS (KOSD1C)	Edwards et al. [10]	356–399	356–399	187–222	100	n/a, +24% emissions
CTL, with CCS (chain 10 WTT)	This study	340	340	203	100	n/a, +24% emissions
GTL	Hendriks et al.[6]	240–480	240–480	152–285	100	n/a, +18% emissions
GTL, by sea (GRSD2)	Edwards et al. [10]	294–324	294–324	172–188	100	n/a, +9% emissions
GTL, no CCS (chain 4 WTT)	This study	316	316	179	100	n/a, +9% emissions
GTL (GRSD2C)	Edwards et al. [10]	308–339	308–339	150–165	100	not listed
GTL, with CCS (chain 9 WTT)	This study	322	322	156	100	−1114
XTL, ex coal and TOPs, with CCS (chain 20 WTT)	This study	342	173	18	51	30

[a] The codes in parenthesis are the exact path identifiers used in the study.
[b] The vehicle was a 2002 diesel (DICI) in this study and in Edwards et al. and from a collection of sources in Hendriks et al.

Table 13
Sources and magnitude of uncertainty in the data and impact on results.

Cause (type of uncertainty)	Magnitude	Impact
Variations in the upstream emissions and energy requirement of feedstock production and supply (unknowable – case specific)	±2% to ±9% [10] >25% [6]	Medium (high if above 10% or so)
Variations in feedstock properties because production methods of biomass and coal vary, as do their compositions (variability)	±3% [27,103]	Medium, affects efficiency
Carbon losses from soil after changing land use to biomass cultivation from (abandoned) grass land (unknowable – case specific)	0–17 years worth of sequestration [10,49]	High, could halve GHG reductions from biomass use
Losses of biomass during storage (lack of data)	3% per month of storage [27]	Medium, more feedstock needed
Variations in feedstock and by-product (electricity, CO_2) prices (unknowable – future development)	±20% to ±40% for feedstock, ±10% for CO_2	High, affects viability
Differences in the actual logistical situation of real plants	Unknown	Probably medium
Variation in the conversion performance of plant components such as gasifiers (lack of data)	±3% [67] or −10% to 0% [14] for gasifiers	Medium, also depends on good practice
Alternative methods of calculating costs (methodology)	0% to +250%	High, can be reduced
Alternative methods of allocating by-products and electricity (methodology)	0% to +50% of CO_2 emissions and cost	High, can be reduced
Uncertainties in cost estimates for conversion plants, and their components (lack of data)	±40% [11,10] +200% [104]	High
Pluriformity in vehicles and driving behaviour of motorists that actually use the diesel (variability)	−50% to +200% [105,106]	Low, applies to all chains
Uncertainties in cost estimates for vehicles (unknowable – future development)	−12% to +14% [107,10]	Low, applies to all chains

Plus™ engineering modelling software[19] (see, for example, [11,14,15]). The absolute results of this study should therefore be used with caution.

The differences in results for different WTW chains are in the same order of magnitude as several of the uncertainties listed above. Some of these uncertainties are associated with methodological choices or lack of data. Such uncertainties could be reduced with further research and by investigating concrete projects. However, it is unclear how results from actual locations, technologies and practices can be made to apply to other situations.

Some sources of uncertainty seem impossible to negate. In the real world, even two identically designed and constructed oil refineries have different efficiency and emissions profiles, due to local requirements and conditions as well as business focus (Janssen [108]). For instance, ambient weather conditions affect the volatility requirements of fuels, leading to product mixes shifting through the year. Substantial situational differences also exist in vehicle emissions, due to variation in driving patterns [106].

Third- and higher order energy inputs, as well as toxic emissions and land use impacts of FT diesel have not been taken into account in this study. It is recommended that research is done to determine significant impacts from these aspects on the desirability of FT diesel. The uncertainties involved in WTW chain analysis make projections inaccurate and these should therefore be used to draw qualitative conclusions only.

5.4. Oil price

In the period from 2004 to mid-2008, oil prices have moved between \$37 and \$139 per barrel. In the longer term, similar fluctuations may be expected [109]. Price projections for the future vary wildly: A 1999 report forecast a high price scenario of \$21 per barrel in 2005, \$28 by 2015 and \$30 by 2020 (in $\$_{1998}$) [110]. In the reference scenarios, the 2006 World Energy Outlook records a price of \$51 per barrel in 2005 and forecasts \$48 for 2015 and \$55 for 2030 (in $\$_{2005}$), while the 2007 WEO forecasts \$70 for 2015 and \$108 for 2030 (in $\$_{2006}$) [86,17]. Shell Oil Co. stated production costs between \$35 and \$65 [111].

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[19] No integration between the ASU and the power island gas turbine is one example of the lack of detail that may influence our results. However, the comparison made in Table 11 and more specific comparisons indicate that our spreadsheet model yields results that are very similar to those arrived at by using Aspen Plus.

The variation in these prices suggests that simple extrapolations of oil prices based on current thinking are not reliable. Also, variations in fuel consumption and the dwindling of surplus production capacity seem to make price stability less likely [112,113].

5.5. Cost of equipment

Literature sources indicated that the variation in the quoted prices for process units is ±30% to ±40% [11,10]. In varying our system choices, we found that the choice of ASU and gasifier alone can cause a 30% change in plant cost. Furthermore, shortage of construction materials and workers can double the price in boom times (see [104]). High costs led ExxonMobil to cancel its GTL project in Qatar in 2007 in favour of an LNG project [114]. We recalculated capital costs to 2005 €.

Depending on circumstances that depend on economic variability rather than technological development, FT diesel could become somewhat cheaper or up to twice as expensive as in our best-guess calculations.

5.6. Environmental benefits of FT diesel

Fischer–Tropsch diesel and current GTL diesel in particular, is touted as environmentally friendly (see, for instance, greencarcongress.com and Shell TV advertisements). While the current generation of GTL diesel is marketed as a clean fossil fuel, this should be clearly understood to apply to local air pollution only, as today's GTL seems to increase CO_2 emissions rather than abate them according to our analyses. The results demonstrate that even with advanced technology (including CCS at the FT plant), the use of CTL will probably increase GHG emissions. XTL and BTL may reduce CO_2 emissions, especially when combined with CCS, but further development of biomass gasification and carbon storage is required before this technology can be applied commercially.

Of particular concern with regard to the 'green' image of BTL fuels, are possible GHG emissions from (indirect) land use changes and biomass cultivation (see [10,115,49,50,52,53]).

On the upside, any FT plant provides a stream of largely pure and storage-ready CO_2 which can be sequestered for around \$6 per tonne, if a suitable reservoir can be found near the site. Potential CCS cases with similar costs have been identified as early opportunities [116].

5.7. Conversion plant locations

One of the questions in selecting viable WTW chains is where to situate conversion plants. Given the high volumes of feedstock, the most efficient way of producing FT diesel seems to be to convert the feedstock to fuel as close to the source as possible. All commercial FT plants to date have been planned and built in the vicinity of feedstocks, rather than consumers. However, these were all constructed at point sources (gas fields and coal mines).

There are several reasons to put an FT plant close to the feedstock source, especially in case of a BTL (and/or CTL) chain:

- Because the volume of feedstock transported decreases as one moves down the chains, fewer logistical facilities are needed to handle the total chain. Port facilities in Western Europe would not have to be expanded several times over. Consequently, the total costs should be lower.
- Creation of industrial facilities in biomass-producing regions would present opportunities for economic development in those regions.
- Investment and operational costs (land rent, labour) in biomass-producing regions will probably be lower than in Western Europe.

There are three reasons to put an FT plant close to the fuel market instead:

1. A source-located FT plant is entirely dependent on a local supply system and it requires a significant investment into a region that may be less developed or less stable region than Western Europe. However, it must be noted that large oil companies have for decades invested in large projects in troubled regions.
2. Biomass production is often seasonal (see [27,101], and FT production at a seasonal source would require ample storage facilities. A plant near the fuel market could use biomass from sources that vary around the year.
3. In case of a further transition to a hydrogen-based economy, it is technically feasible to 'unhook' the FT synthesis train and shift the entire volume of syngas to H_2. The majority of a conversion plant investment would therefore be robust even if future developments go against the Fischer–Tropsch option. Distributing this hydrogen would be easier if the plant were located close to the consumers.

Also of importance is the FT-naphtha, a by-product of FT synthesis that could be a valuable feedstock for chemical industries. These industries are commonly located near oil refineries. Depending on how a transition is made from fossil to FT, this could be either a business opportunity or lead to capital losses. The choice of locations for FT production, together with a reduced oil consumption, can cause a geographical shift of economic activity in the fuel sector.

6. Conclusions

We calculated carbon and energy flows in 14 models of FT plants. Representations of various gasifiers, FT synthesis units and other process units were constructed and incorporated. Based on the sizes of the various process flows, factored estimation was used to derive investment costs. The FT plants where then combined with data on coal and natural gas supply, biomass production, conversion to biomass intermediaries such as pellets or TOPS, transport costs, vehicle costs and GHG emissions to arrive at 17 complete WTW chains.

Based on technological developments described in literature, we framed assumptions for these developments until 2020. These include moving towards biomass conversion at the source, improvements in process efficiency, and the use of CCS.

Important uncertainties, to order of tens of percents, were found in the data for component costs, variability in prices of feedstocks and by-products, and the GHG impact of producing biomass. It is impossible to fix such case-specific data in ex-ante assessments, unlike methodological choices and technical data. This study has not been able to reduce the ranges of the uncertainty in WTW studies (some seem to have expanded), but we have catalogued the sources of uncertainty (see Table 13). Given the extent of the uncertainties that we and others have found, cost and GHG emission values for Fischer–Tropsch diesel should be interpreted as best-guess estimates within uniform ranges of uncertainty.

Costs of FT diesel depend in large part on feedstock prices and conversion plant efficiency. GTL is competitive with oil-based diesel in terms of cost, breaking even at an oil price equivalent of \$34/bbl. For CTL, the oil price equivalent cost is found to be \$60/bbl. For BTL, feedstock costs would have to come down or oil prices be above \$75/bbl. At the same time, fuel costs comprise only 5–17% of the total cost of driving.

GHG emissions from FT diesel depend almost completely on the efficiency of conversion plants, the efficiency of conversion to biomass intermediates, and the feedstock used. CTL and, to a lesser extent, GTL chains without CCS were found to increase our transport-related GHG emissions. GTL with CCS was found to reduce GHG emissions by around 5% compared to fossil diesel. The net emissions from BTL can be an order of magnitude smaller and can be made negative by application of CCS.

It is possible to have net climate neutral driving by using around 50% BTL with CCS, combined with other fuels, if biomass gasification and carbon sequestration can be made to work on an industrial scale and the feedstock is obtained in a sustainable (climate-neutral) manner. Further reductions in GHG emissions may come from improvements in conversion plants and supply logistics, as well as reducing improving the fuel economy of cars.

Like hydrogen, Fischer–Tropsch fuels should be considered as an intermediate to put natural gas, (clean) coal or biomass into the fuel tank of an automobile. The evidence suggests that it is worth to further explore FT chains that use the latest in technology and conversion as early in the chain as possible. In practice this would mean FT plants with CCS, either in the country of origin of the feedstock, or using a more easily processed intermediate such as TOPS over biomass pellets. However, many uncertainties will remain until the actual implementation of such strategies.

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